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ORIGINAL PAPER

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STABILITY ANALYSIS OF MAMAK DAM BEHAVIOUR UNDER VARIOUS WATER LEVELS IN THE RESERVOIR

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ABSTRACT

A dam is an engineered construction designed to store water primarily for human needs. When a dam fails, it has the potential to become a substantial disaster. Some primary causes of dam failure are excessive water leakage, landslides and earthquakes. In general, the current performance evaluation of the Mamak Dam falls into the "fairly good" category, even in the aftermath of the earthquake event with a magnitude of 6.5 Mw in 2018. In this study, the dam's stability is analysed under seismic events, rapid drawdown and maximum daily rainfall infiltration. It is concluded that the upstream and downstream slopes were generally found to be safe in all design situations. Nevertheless, the impact of the maximum design earthquake (MDE) is notable in both pseudo-static and dynamic analyses, causing a reduction of over 50% in the factor of safety (FoS) – ultimately falling below the minimum safety threshold. Conversely, the operating basis earthquake (OBE) has a relatively minor effect on the FoS.

Keywords: dam stability, pseudo-static analysis, dynamic analysis, maximum design earthquake, MDE

INTRODUCTION

Apart from being a crucial resource to meet human needs, dams also have the potential to cause significant disasters if they fail (International Commission on Large Dams [ICOLD], 2019). A dam collapse can lead to devastating flash floods, resulting in extensive losses such as loss of lives, property, infrastructure and environmental devastation (Utepov et al., 2022). A study by the Indonesian Dam Safety Commission on 122 embankment dams revealed that 20% are considered at risk. Among these vulnerable dams, 59% have been in operation for over 25 years, while the remaining 41% are younger than 25 years (Komisi Keamanan Bendungan [KKB], 2020).

The Indonesian Agency for Meteorology, Climatology, and Geophysics have documented a long history of frequent and devastating earthquakes with a magnitude exceeding 6 Mw on Sumbawa Island from 1821 to 2021 (Badan Meteorologi Klimatologi dan Geofisika [BMKG], 2021). These seismic events have had severe consequences, leading to significant loss of life and extensive damage to infrastructure (Adi Kurniawan, Suarbawa & Septiadhi, 2017). Therefore, it is crucial to conduct a thorough seismic hazard analysis of Sumbawa Island to proactively address potential damages (Santoso & Agustawijaya, 2020). This study aims

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to evaluate dam stability during earthquakes and recommend measures if stability or water leakage becomes a concern. The analysis of dam stability includes operating basis earthquake (OBE) and maximum design earthquake (MDE), rapid drawdown and maximum daily rainfall intensity.

LITERATURE REVIEW

Pseudo-static analysis

This analysis emulates the effects of an earthquake's shaking by introducing an acceleration force that generates inertial forces. These inertial forces, which exert significant influence on the stability of embankment slopes, operate in both horizontal F_h and vertical F_v directions, acting at the centre of each segment. These forces are described as (Himanshu & Burman, 2019):

$$F_h = \left(\frac{a_h W}{\mathrm{g}} \right) = k_h W, \tag{1}$$

$$F_v = \left(\frac{a_v W}{\mathrm{g}} \right) = k_v W, \tag{2}$$

where:
F_h – inertial force in horizontal direction [N],
F_v – inertial force in vertical direction [N],
a_h – horizontal pseudo-static acceleration [m·s^{-2}],
a_v – vertical pseudo-static acceleration [m·s^{-2}],
W – weight of the slice [kg],
g – constant gravitational acceleration [m·s^{-2}],
k_h – horizontal seismic coefficient [-],
k_v – vertical seismic coefficient [-].

When seismic loading is taken into account, the determination of S_{res} and S_{mob} can be carried out in the following manner

$$S_{\mathrm{res}} = c' + \left(N - \mu - F_h \cos\alpha \right) \tan\phi', \tag{3}$$

$$S_{\mathrm{mob}} = W \sin\alpha + F_h \cos\alpha, \tag{4}$$

where:
S_{res} – seismic resistance coefficient [-],
S_{mob} – seismic mobilised load coefficient [-],
c' – effective soil cohesion [-],
N – number calculated as W multiplied by the cosine of α,
μ – pore water pressure [kPa],
α – inclination of the base [°],
ϕ' – effective frictional angle [°].

Dynamic analysis

Many geotechnical engineering problems – like those related to structures such as retaining walls, tunnels, earth dams, and embankments – are typically analysed using two-dimensional dynamic simulations utilising the finite element method (FEM). The equation describing the motion of elements is provided as follows:

$$[M]\{\ddot{U}\}+[C]\{\dot{U}\}+[K]\{U\}=\{R(t)\}, \tag{5}$$

where:
$[M]$ – mass matrix,
$[C]$ – damping matrix,
$[U]$ – axial displacement of nodal points within the model,
$[K]$ – stiffness matrix, including the material and geometric nonlinearities,
$\{R(t)\}$ – axial forces acting on the model's points.

The Newmark step-by-step method is a contemporary approach employed for solving motion equations, particularly in the context of dynamic seismic analysis. This method was first introduced by Newmark in 1965. It involves calculating displacement and velocity through the utilization of the following equations:

$$u_{t+\Delta t}=u_t+\dot{u}_t\Delta t+\left[\left(\frac{1}{2}-\alpha\right)\ddot{u}+\alpha\ddot{u}_{t+\Delta t}\right]\Delta t^2, \tag{6}$$

$$\dot{u}_{t+\Delta t}=\dot{u}_t+\left[(1-\beta)\ddot{u}_t+\beta\ddot{u}_{t+\Delta t}\right]\Delta t, \tag{7}$$

where:
u_t – displacement vector at time t,
$\dot{u}_t$ – velocity vector at time t,
$\ddot{u}_t$ – acceleration vector at time t.

The stability of the solution in accordance with the implicit Newmark scheme (as outlined by Hu in 1997) relies on certain parameters. These parameters, namely Δt (representing the time increment) and α and β (acting as control parameters for numerical accuracy), must conform to specific conditions to ensure a stable solution. Such a condition is:

$$\beta\geq 0.5;\ \alpha\geq 0.25(0.5+\beta)^2. \tag{8}$$

In the conventional Lagrange's method, as described by Chaudhary and Bathe in 1986, setting β to 0.5 yields satisfactory results in the calculations. The average acceleration method is also employed alongside Newmark's method to solve the motion equations.

To prevent undesired wave reflections at the model boundaries, it is necessary to lay down specific boundary conditions. These conditions are established following the principles of the Lysmer–Kohlmeyer's model, which dictates the computation of the normal stress and shear stress absorbed by a damper as outlined as follows (Brinkgreve & Vermeer, 1998).

$$\sigma_n=-c_1\rho V_P\dot{u}_x, \tag{9}$$

$$\tau=-c_2\rho V_S\dot{u}_y, \tag{10}$$

where:
σ_n – normal stress [N·m^{-2}],
c_1 – relaxation coefficient employed to enhance wave absorption in the normal direction at the boundary [-],
ρ – mass density [kg·m^{-3}],

V_P – longitudinal wave velocity [m·s^{-1}],
$\dot{u}_x$ – particle motion velocity in the x direction [m·s^{-1}],
τ – shear stress [Pa],
c_2 – relaxation coefficient employed to enhance wave absorption in the tangential direction at the boundary [-],
V_S – shear wave velocity [km·s^{-1}],
$\dot{u}_y$ – particle motion velocity in the y direction [m·s^{-1}].

Determination of seismic load

The process of establishing the design earthquake magnitude for earth dams includes evaluating the safety risk factor based on ICOLD (2018) and the Indonesian guidelines for stability analysis of earth-fill dams under seismic loads (Department of Human Settlements and Regional Infrastructure, 2004). According to the provided description, the weight factor is determined to assess the total risk factor (Fr_{tot}) as indicated in Table 1.

Considering the risk class, the Mamak Dam is designated with an OBE with a return period of 100–200 years and a MDE with a return period of 10,000 years. The earthquake coefficient method is employed for analysis. The analysis procedure follows the Indonesian Guidelines for stability analysis of earth-fill dams due to seismic loads (Department of Human Settlements and Regional Infrastructure, 2004).

Modified earthquake coefficients by Indonesia seismic hazard map

In the analysis of earthquake coefficients using the 2017 Indonesian earthquake zone map, the process involves determining earthquake acceleration at the base rock by considering dam location and frequency. For the Mamak Dam with acid tuff and welded tuff (hard rock), the site class coefficient (F_{PGA}) is equal to 0.8. A summary of the horizontal and vertical modified earthquake coefficients is shown in Table 2.

Table 1. Dam safety evaluation criteria for risk factor

Risk impact	Weight factor	Risk class/Importance	
Reservoir capacity (ML×10^3)	4	$60 > C > 2.0$	high
Dam height [m]	5	$500 < L < 2\,000$	high and strong importance
Evacuation requirements – number of persons (amended as per Reference 3)	12	no emergency action plan (12)	extreme importance
Potential downstream damage (to existing structures)	13	major national highway/interstate/ /power station	high and strong importance
Availability of construction and maintenance records	3	no procedures	extreme importance
Availability of processed instrumentation and surveillance records	3	no data	extreme importance
Level of effort extended in previous safety evaluations	2.5	reports submitted irregularly	high and strong importance
New or future downstream development	0.5	local planning in place	equal importance
Flood capacity-related deficiencies	2	concrete gravity	moderate importance
Static stability-related deficiencies	6	active surface seepage	moderate importance
Earthquake resistance-related deficiencies	8	peak ground acceleration beyond 0.25 g and no fault within 10 km	high
Total score (Fr_{tot})		59	
Risk class of the Mamak Dam		(111) high	

Source: PT. Virama Karya (2020).

Table 2. Summary of horizontal seismic coefficient (k_h) and vertical seismic coefficient (k_v)

Return period (T) [s]	$y = 0.25\ h$		$y = 0.5\ h$		$y = 0.75\ h$		$y = h$	
	k_h	k_v	k_h	k_v	k_h	k_v	k_h	k_v
200	0.204	0.082	0.170	0.068	0.155	0.062	0.140	0.056
10 000	0.571	0.228	0.476	0.190	0.434	0.174	0.392	0.157

Source: Halim (2023).

CHARACTERISTICS OF THE MAMAK DAM

The Mamak Dam was constructed in 1990 in Mamak Village, Sumbawa Island, Indonesia, at coordinates 117°34′42″ East and 8°41′29.2″ South. The Mamak Dam serves multiple functions, including hydropower generation, irrigation, and local water supply. The Mamak Dam has four embankments – namely, the main dam, Saddle Dam-1, Saddle Dam-2 and Saddle Dam-3 (Fig. 1). The Mamak Dam is composed of several essential elements – the impervious core (constructed from earth fill), filter layer, transition layer, random rock, selected rock and rock fill (Fig. 2).



Fig. 1. Bird's view of the Mamak Dam

Source: PT. Raya Konsult (2022a).

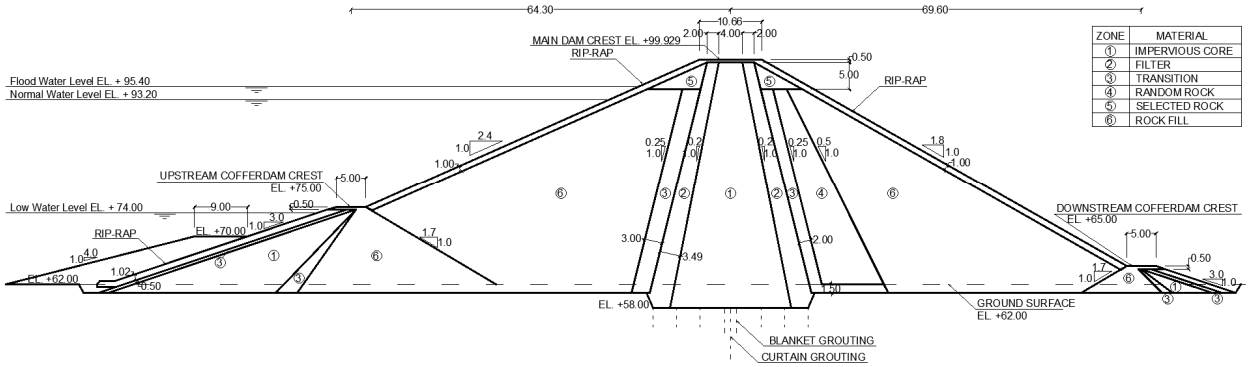


Fig. 2. Cross-section A–A of the Mamak main dam

Source: Halim (2023).

The Mamak Dam covers a catchment area of 108 km^2. When at full water level (FWL), it can hold 29.839 million m^3 of water, with a live storage capacity of 27.671 million m^3, along with a dead storage capacity of 2.167 million m^3. At flood water level (FWL), the water spread area is 2.357 km^2. Key water level benchmarks include FWL at elevation +95.40 m, normal water level (NWL) at elevation +93.43 m and low water level (LWL) at elevation +74.00 m. The deepest bed level is recorded at elevation +58.00 m. The main dam, along with its cofferdams, reaches a height of 36.959 m, with a crest level of elevation +99.93 m, extending over a length of 203.01 m and a crest width of 10.66 m. Additional saddle dams are Saddle Dam-1 (33.929 m tall, crest level elevation +99.93 m, 205.394 m long, crest width 10.245 m), Saddle Dam-2 (10.929 m tall, crest level elevation +99.56 m, 54.611 m long, crest width 9.832 m) and Saddle Dam-3 (16.538 m tall, crest level elevation +99.80 m, 85.986 m long, crest width 10.154 m), as detailed by PT. Raya Konsult (2022b).

Earthquake records in the Mamak Dam

In seismic analysis, two distinct ground acceleration time histories specific to the location are utilised (Fig. 3). The maximum ground acceleration in the horizontal (x) and vertical (y) directions are 0.550 times the acceleration due to gravity (0.550 g) and 0.363 times the acceleration due to gravity (0.363 g), respectively.

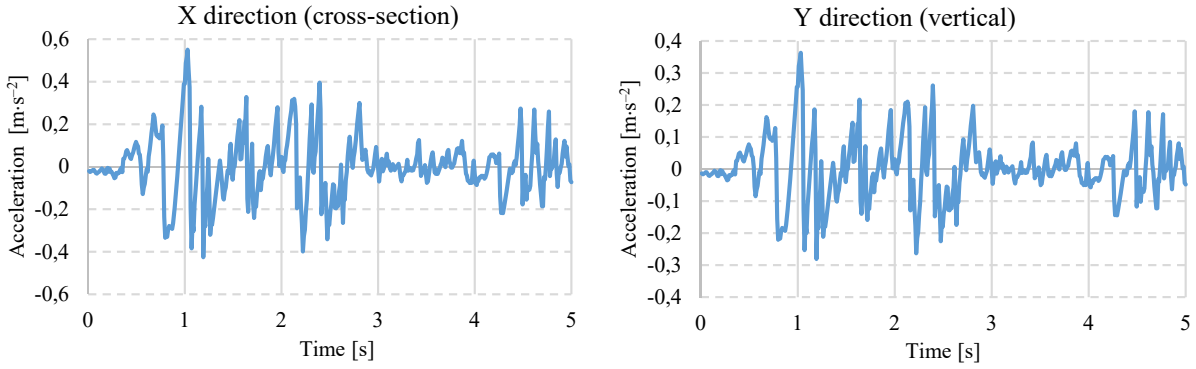


Fig. 3. Accelerometer used in dynamic analysis of the Mamak Dam

Source: PT. Raya Konsult (2022c).

Rainfall intensity in the Mamak Dam area

In order to investigate the effect of any climatic changes on the slope stability of the Mamak Dam, the maximum average daily rainfall was collected from PT. Raya Konsult (2022b) and is given in Table 3. Based on Table 3, the assumed precipitation intensity is 0.164 m daily.

Table 3. Maximum average daily rainfall in the Mamak Dam area

No	Year		Maximum daily rainfall [mm]
1	1996		80
2	1997		116
3	1998		130
4	1999		130
5	2000		109
6	2001		72
7	2002		100
8	2003		103
9	2004		87
10	2005		106
11	2006		82
12	2007		60
13	2008		68
14	2009		147
15	2010		112
16	2011		79
17	2012		96
18	2013		64
19	2014		164
20	2015		51
21	2016		118
22	2017		95
23	2018		98
24	2019		93
25	2020		86
		Max	164
		$\sum$	2 445
		AVG	98

Source: PT. Raya Konsult (2022b).

Geotechnical design parameters

To provide a refined set of inputs for the numerical model, geotechnical parameters are organised based on the designated zones typically found in embankment dams. The geotechnical parameters of the main dam, Saddle Dam-1, Saddle Dam-2, Abutment-1 and Abutment-2 – which are implemented in the numerical model – are given in Table 4.

Table 4. Geotechnical parameters of the Mamak Dam

Type	Zone	Soil classification	Saturated permeability coefficient (k_s) [m·s^{-1}]	Zone area ($A = k_y/k_x$) [m^2]	Unit weight (γ) [kN·m^{-3}]	Effective cohesion (c') [kPa]	Effective frictional angle (φ') [°]
Embankment zone	earth-fill zone	clay	5.82E-06	0.5	17.52	12.00	27.10
	filler zone	sand	3.28E-03	1.0	20.90	0	32.00
	transition zone	sand	3.60E-02	1.0	18.09	0	28.14
	random zone	clay	3.80E-04	1.0	18.90	6.00	30.10
	selected rock	rock	–	1.0	18.67	0	37.00
	rock-fill zones	rock	–	0.4	21.70	4.15	36.15
	rip-rap	rock	3.30E-03	1.0	25.00	5.00	37.00
Abutment	Abutment-1 Abutment-2	clay	1.00E-04	1.0	17.11	2.30	28.75
Foundation	downstream area	clay	1.00E-04	1.0	18.00	35.00	41.00
	below DS	sandy clay	1.00E-04	1.0	17.04	10.00	32.00

Source: PT. Raya Konsult (2022a).

The assessment of stability is conducted for both the slopes on the upstream and downstream sides of each embankment (Fig. 4). Then, the outcomes of the analysis are compared with the safety standards and guidelines.

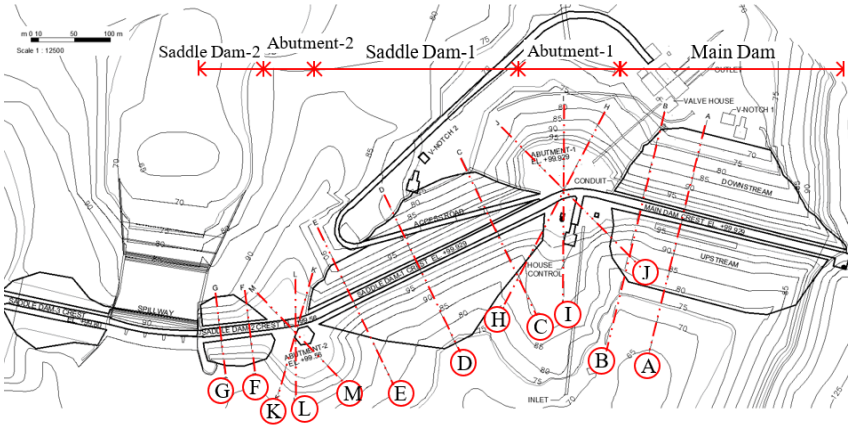


Fig. 4. Location of the cross-sections on the dam plane for slope stability

Source: Halim (2023).

ANALYSIS OF RESULTS

Pseudo-static analysis results

In the upstream slope, cross-sections A–M exhibit FoS values ranging from approximately 1.737 to 3.740 in the absence of earthquakes, indicating generally stable conditions in the area of the main dam, Saddle Dam-1, Saddle Dam-2, Abutment-1 and Abutment-2 (Table 5). The inclusion of earthquake considerations results in decreased FoS values for these sections. With the effect of OBE, FoS obtained by each cross-section ranges from 1.197 to 1.881. The FoS of the whole cross-sections further decreases with MDE earthquake effects, and none of them are considered as safe.

In the downstream slope, cross-sections A–M maintain FoS values above 1.2 without earthquakes, indicating acceptable stability, except for cross-sections H and I (Abutment-1) due to a higher slope inclination. Decreasing the slope inclination is needed. Similar to upstream slopes, the FoS of the whole cross-sections for upstream slope stability analysis further decreases with MDE earthquake effects, and only one of them is considered safe, which is Abutment-2 because the height of Abutment-2 is not as high as other dam parts. It is evident that earthquake effects significantly decrease the FoS for all sections, warranting the implementation of appropriate engineering measures to enhance long-term slope stability.

Table 5. Pseudo-static analysis during normal water level

Cross-section	Upstream slope stability analysis			Downstream slope stability analysis		
	FoS without earthquake	FoS with earthquake (OBE)	FoS with earthquake (MDE)	FoS without earthquake	FoS with earthquake (OBE)	FoS with earthquake (MDE)
A	2.237	1.282	0.736	1.651	1.251	0.855
B	1.938	1.286	0.818	1.275	0.992	0.735
C	2.151	1.332	0.802	1.347	1.029	0.739
D	2.079	1.428	0.918	1.670	1.248	0.865
E	2.223	1.507	0.994	1.586	1.219	0.854
F	2.203	1.528	0.990	1.649	1.215	0.818
G	2.208	1.505	1.015	1.721	1.292	0.883
H	2.954	1.488	0.825	1.135	0.787	0.563
I	3.740	1.881	1.011	1.115	0.459	0.323
J	3.180	1.700	1.058	1.532	1.157	0.894
K	3.444	1.622	0.923	2.488	1.705	1.103
L	2.392	1.357	0.791	2.682	1.525	0.965
M	1.910	1.197	0.718	2.190	1.553	1.033

FoS – factor of safety, OBE – operating basis earthquake, MDE – maximum design earthquake.

Source: Halim (2023).

In this study, a comprehensive slope stability analysis was conducted on both the upstream and downstream slopes of the Mamak Dam. The analysis included pseudo-static analysis under normal conditions – without earthquake effects – as well as conditions with earthquake effects, specifically for the OBE and MDE. Additionally, a rapid drawdown scenario was considered, with a 12-day duration for the water level to decrease from the FWL to the LWL. To assess the stability during drawdown, three specific days (Day 4, Day 8 and

Day 12) were selected for evaluation, representing critical stages in the drawdown process. On day 4, the water level dropped from the FWL at elevation 95.40 m to 88.26 m. By Day 8, the water level had further decreased to 81.14 m, and by Day 12, it had reached the LWL at 74.00 m.

The results of the analysis indicated that both the normal condition (without earthquake effects) and the scenario with OBE produced safe outcomes, with acceptable values of FoS. However, the analysis with MDE showed unsafe results, indicating that the embankment would likely fail under such seismic conditions. The findings suggest that while rapid drawdown alone does not significantly affect the dam's stability, the combination of rapid drawdown with an MDE event could lead to dam failure. Therefore, the critical condition for this dam is the simultaneous occurrence of rapid drawdown and a major earthquake (MDE), which could compromise the safety of the structure. The analysis of results during rapid drawdown from flood water level to low water level on Day 12 are given in Table 6.

Table 6. Analysis due to rapid drawdown from flood water level to low water level T-12

Cross-section	Upstream slope stability analysis			Downstream slope stability analysis		
	FoS without earthquake	FoS with earthquake (OBE)	FoS with earthquake (MDE)	FoS without earthquake	FoS with earthquake (OBE)	FoS with earthquake (MDE)
A	1.856	1.226	0.768	1.802	1.373	0.944
B	1.964	1.425	0.950	1.535	1.187	0.833
C	1.725	1.240	0.838	1.506	1.144	0.812
D	2.060	1.443	0.942	1.639	1.222	0.847
E	2.244	1.585	1.039	1.661	1.249	0.854
F	2.202	1.529	0.992	1.649	1.215	0.818
G	2.297	1.623	1.064	1.721	1.292	0.883
H	2.149	1.357	0.882	1.320	1.112	0.716
I	2.343	1.531	0.969	1.221	0.928	0.660
J	2.241	1.479	1.023	1.893	1.394	1.026
K	2.663	1.619	1.025	2.488	1.705	1.103
L	2.209	1.541	1.058	3.399	1.891	1.144
M	1.627	1.211	0.832	2.190	1.553	1.033

FoS – factor of safety, OBE – operating basis earthquake, MDE – maximum design earthquake.

Source: Halim (2023).

Dynamic analysis results

The results of the dynamic analysis, considering factors of safety (FoS) for upstream and downstream slopes under varying water elevations (FWL, NWL, LWL), present concern regarding the stability of the evaluated cross-sections. In accordance with established engineering standards such as DIN 19700-12 (Deutsche Institut für Normung [DIN], 2004), the minimum required FoS for slope stability is 1.1. Most of the cross-sections did not meet the required minimum FoS due to the impact of MDE (Table 7).

Table 7. Dynamic analysis results (maximum design earthquake)

Cross-section	Flood water level		Normal water level		Low water level	
	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope
A	0.708	0.814	0.711	0.830	0.919	0.790
B	0.790	0.675	0.793	0.728	0.925	0.808
C	0.772	0.694	0.777	0.728	0.868	0.830
D	0.865	0.806	0.893	0.840	0.917	0.840
E	0.949	0.829	0.969	0.829	–	–
F	0.932	0.793	0.965	0.793	–	–
G	0.971	0.858	0.990	0.858	–	–
H	0.793	0.505	0.800	0.538	0.793	0.505
I	0.975	0.232	0.986	0.298	0.980	0.658
J	1.036	0.849	1.033	0.869	1.025	1.030
K	0.891	1.078	0.898	1.078	–	–
L	0.751	0.911	0.766	0.940	–	–
M	0.663	1.008	0.693	1.008	–	–

FoS – factor of safety.

Source: Halim (2023).

Conversely, the OBE had a relatively minor effect on FoS value, with all cross-sections under OBE conditions considered to be safe (Table 8).

Table 8. Dynamic analysis results (operating basis earthquake)

Cross-section	Flood water level		Normal water level		Low water level	
	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope
A	1.266	1.206	1.257	1.226	1.291	1.348
B	1.284	0.914	1.261	0.967	1.400	1.175
C	1.315	0.979	1.307	1.004	1.333	1.224
D	1.394	1.160	1.403	1.223	1.418	1.223
E	1.515	1.152	1.482	1.194	–	–
F	1.482	1.190	1.503	1.190	–	–
G	1.493	1.267	1.480	1.267	–	–
H	1.459	0.710	1.463	0.762	1.459	0.710
I	1.849	0.332	1.856	0.434	1.565	0.936

Table 8 (cont.)

Cross-section	Flood water level		Normal water level		Low water level	
	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope	FoS upstream slope	FoS downstream slope
J	1.699	1.102	1.675	1.132	1.508	1.416
K	1.613	1.680	1.597	1.680	–	–
L	1.331	1.440	1.332	1.500	–	–
M	1.155	1.528	1.172	1.528	–	–

FoS – factor of safety.

Source: Halim (2023).

Rainwater infiltration-based stability assessment results

In terms of rainwater infiltration-based stability assessment, FoS values without the impact of earthquake and rainfall infiltration and FoS values with the impact of only rainfall infiltration exceed the required minimum FoS (1.2–1.5), indicating that the whole structure of the dam remains stable during heavy rainfall, although flooding is occurring. However, when it comes to the OBE with rainfall infiltration, the FoS in the cross-sections of the main dam and Abutment-1 falls below safety criteria. Furthermore, with the impact of MDE and rainfall infiltration, most of the cross-sections do not meet the required minimum FoS (Table 9).

Table 9. Rainwater infiltration-based stability assessment during flood water level

Cross-section	FoS without earthquake and rainfall infiltration	FoS with rainfall infiltration	FoS with earthquake (OBE) and rainfall infiltration	FoS with earthquake (MDE) and rainfall infiltration
A	1.599	1.533	1.477	1.000
B	1.626	1.563	1.158	1.000
C	1.824	1.722	1.155	1.000
D	2.317	2.147	1.267	1.000
E	4.208	3.750	1.776	1.000
F	2.856	2.288	2.580	2.238
G	5.474	4.771	3.522	1.721
H	1.599	1.494	1.122	1.000
I	1.649	1.501	1.172	1.000
J	1.649	1.499	1.160	1.000
K	3.704	3.519	1.809	1.000
L	4.404	3.618	1.821	1.000
M	3.750	3.438	1.969	1.000

FoS – factor of safety, OBE – operating basis earthquake, MDE – maximum design earthquake.

Source: Halim (2023).

It was observed that the pore water pressures generated due to rainwater infiltration added to the seepage, resulting in deformations of the dam faces and reducing the stability of the earthen dams. Heavy rainfall can lead to the occurrence of overtopping in dams. To prevent overtopping in dams, there is a concept known as early release – this concept involves a policy suggesting the construction of gates in the spillway. The flood is predicted based on hydrological data. The minimum freeboard is analysed afterwards. The condition of early release is meant to prevent situations where the water level exceeds 50% of the minimum freeboard.

CONCLUSIONS

This study provides stability analysis based on a case study of the Mamak Dam. Analyses were conducted on both the inclining side facing the reservoir and the declining side of the earth embankment across a total of 13 different sections. The analyses included an examination of the slopes for both continuous seepage conditions (steady state) and temporary seepage conditions (transient state) to simulate rapid drawdown conditions and the impact of rainwater infiltration. Also, seismic loading impact was accounted for through both pseudo-static and dynamic analysis methods. Two values of horizontal seismic coefficients (k_h), two values of vertical seismic coefficients (k_v) and two independent ground acceleration time histories were considered in the analyses. The design situations of each cross-section encompassed different water elevations, rapid drawdown, seismic loadings and rainfall intensity.

The following conclusions have been drawn from the present work:

– The upstream and downstream slopes of all cross-sections have been generally found safe for slope stability analysis in different water elevation cases, rapid drawdown and rainfall intensity design situations. Nevertheless, the simultaneous occurrence of a major earthquake (MDE) and each case significantly decreases the FoS for all sections.
– The impact of the MDE was notable in both pseudo-static and dynamic analyses, causing a reduction of over 50% in the FoS for static and dynamic conditions – ultimately falling below the minimum safety threshold. Conversely, the OBE had a relatively minor effect on the FoS value, with all cross-sections under OBE conditions considered to be safe.
– The rainwater infiltration-based stability assessment shows that the Mamak Dam remains stable during heavy rainfall, even in flooding conditions. However, when rainfall infiltration is combined with an OBE, the FoS in the main dam and Abutment-1 falls below safety criteria. Under the combined effects of MDE and rainfall infiltration, most cross-sections fail to meet the required FoS, indicating a significant risk to the dam's stability during such extreme events.

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Authors' contributions

Conceptualisation and methodology: Z.L., M.L. and N.H.; validation: N.H.; formal analysis: N.H.; investigation: N.H.; resources: N.H.; data curation: N.H.; writing – original draft preparation: N.H.; writing – review and editing: Z.L., M.L. and N.H.; visualisation: N.H.; project administration: N.H.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Adi Kurniawan, M., Suarbawa, K. N. & Septiadhi, A. (2017). Analysis of earthquake disaster risk in the West Nusa Tenggara region. *Physics Bulletin*, *18* (1), 38. https://doi.org/10.24843/bf.2017.v18.i01.p07

Badan Meteorologi Klimatologi dan Geofisika [BMKG], (2021). *Indonesian Earthquake Catalog: Relocation of Hypocenters and Tectonic Implications*. Jakarta: The Indonesian Geophysics and Climatology Agency.

Brinkgreve, R. B. & Vermeer, P. A. (1998). Finite element code for soil and rock analyses. In *Plaxis Version 7.2 Manual*. Rotterdam–Brookfield–Rotterdam: AA Balkema.

Chaudhary, A. B. & Bathe, K. J. (1986). A solution method for static and dynamic analysis of three-dimensional contact problems with friction. *Computers and Structures*, *24* (6), 855–873. https://doi.org/10.1016/0045-7949(86)90294-4

Department of Human Settlements and Regional Infrastructure (2004). *Stability analysis of earthfill dam due to seismic load. In Guidelines for Construction and Buildings* (Pd T-14-2004-A). Jakarta: Ministry of Public Works and Housing (MPWH).

Deutsche Institut für Normung [DIN], (2004). *Stauanlagen. Teil 12: Hochwasserrückhaltebecken* (DIN 19700-12). Berlin: Deutsche Institut für Normung.

Halim, N. (2023). *Analysis of Mamak Dam behavior under different water levels in the reservoir* (MSc thesis). Warsaw University of Life Sciences, Warsaw.

Himanshu, N. & Burman, A. (2019). Seepage and stability analysis of Durgawati Earthen Dam: A case study. *Indian Geotechnical Journal*, *49* (1), 70–89. https://doi.org/10.1007/s40098-017-0283-1

Hu, N. (1997). A solution method for dynamic contact problems. *Computers and Structures*, *63* (6), 1053–1063. https://doi.org/10.1016/S0045-7949(96)00408-7

International Commission on Large Dams [ICOLD], (2018). *Flood Evaluation and Dam Safety.* Bulletin 170. Paris.

International Commission on Large Dams [ICOLD], (2019). *World Declaration on Dam Safety*. Porto.

Komisi Keamanan Bendungan [KKB], (2020). *Dam Operational Improvement and Safety Project (DOISP)*. Jakarta: The Indonesian Dam Safety Commission.

Newmark, N. M. (1965). Effects of earthquakes on dams and embankments. *Geotechnique*, *15* (2), 139–160. https://doi.org/10.1680/geot.1965.15.2.139

PT. Raya Konsult (2022a). *Geological & geotechnical investigation report of Mamak Dam. In Preparation & Legalization of Dam Operational Permit in Sumbawa I Island*. Jakarta: Ministry of Public Works & Housing (MPWH).

PT. Raya Konsult (2022b). *Hydrology report of Mamak Dam. In Preparation & Legalization of Dam Operational Permit in Sumbawa I Island*. Jakarta: Ministry of Public Works & Housing (MPWH).

PT. Raya Konsult (2022c). Mamak Dam safety evaluation report. In Preparation & Legalization of Dam Operational Permit in Sumbawa I Island. Jakarta: Ministry of Public Works & Housing (MPWH).

PT. Virama Karya (2022). *Determination & summary of the final risk score and risk category. In Dam Operational Improvement and Safety Project – Phase II*. Jakarta: Ministry of Public Works & Housing (MPWH).

Santoso, C. B. & Agustawijaya, D. S. (2020). Seismic risk for Sumbawa Island based on seismicity and peak ground acceleration. *IOP Conference Series: Earth and Environmental Science*, *413* (1). https://doi.org/10.1088/1755-1315/413/1/012009

Utepov, Y., Lechowicz, Z., Zhussupbekov, A., Skutnik, Z., Aldungarova, A., & Mkilima, T. (2022). The Influence of Material Characteristics on Dam Stability Under Rapid Drawdown Conditions. *Archives of Civil Engineerin*g, *68* (1), 539–553. https://doi.org/10.24425/ace.2022.140184

ANALIZA STATECZNOŚCI ZAPORY MAMAK PRZY RÓŻNYM POZIOMIE WODY W ZBIORNIKU

STRESZCZENIE

Zapora ziemna jest konstrukcją inżynierską, którą projektuje się w celu retencjonowania wody głównie na potrzeby ludzkie. W przypadku awarii zapory istnieje ryzyko wywołania znacznych strat ludzkich, ekonomicznych i środowiskowych. Główne czynniki prowadzące do uszkodzeń zapory to między innymi niekontrolowane przecieki, osuwiska i trzęsienia ziemi. Ogólny stan stateczności zapory Mamak wpisuje się w kategorię „akceptowalny", nawet po trzęsieniu ziemi o magnitudzie 6,5 Mw w 2018 roku. W niniejszej pracy przeanalizowano stateczność zapory podczas zdarzeń sejsmicznych, szybkiego obniżania wody w zbiorniku oraz maksymalnej dziennej intensywności opadów deszczu. Stwierdzono, że skarpy od strony górnej i dolnej wody były bezpieczne we wszystkich sytuacjach projektowych. Niemniej jednak wpływ maksymalnego trzęsienia ziemi o projektowanej wielkości (MDE) jest zauważalny zarówno w analizach pseudostatycznych, jak i dynamicznych, prowadząc do zmniejszenia współczynnika stateczności (FoS) o ponad 50%, ostatecznie poniżej minimalnego progu bezpieczeństwa. Z kolei trzęsienie ziemi o działaniach operacyjnych (OBE) ma stosunkowo niewielki wpływ na FoS.

Słowa kluczowe: stateczność zapory, analiza pseudostatyczna, analiza dynamiczna, maksymalne trzęsienie ziemi o projektowanej wielkości, MDE

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ENGINEERING AND PHYSICAL BASES AND ENVIRONMENTAL SAFETY OF PLASMO-CHEMICAL DISPOSAL OF HAZARDOUS MEDICAL WASTE

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ABSTRACT

The unrestrained growth in the amount and rate of production of hazardous medical waste in the context of the Russian-Ukrainian war critically exacerbates the environmental situation in Ukraine. At the same time, existing traditional methods and technological means are not able to ensure their complete environmentally safe processing and disposal. The paper considers an alternative high-temperature technology for plasma--chemical pyrolysis of medical waste at 1,100−1,250°C, which is implemented in the form of a Plazmon-3 mobile plasma pyrolysis unit, designed and built based on the PUN-1 domestic universal plasma generator. The paper also describes the design, principle of operation, engineering and physical principles underlying the creation of the Plazmon-3, designed to dispose of any type and category of medical waste by destroying it under the action of a high-temperature plasma torch generated by the PUN-1 DC plasma generator, as well as its main operational characteristics. Air, nitrogen, argon, helium, and other gases can be used as plasma-forming gases for the installation. The paper describes the advantages of using high-temperature plasma-chemical pyrolysis for the disposal of hazardous medical and other wastes, which make this technology, in terms of its environmental safety, beyond competition and, unlike its smoke-emitting counterparts, capable of destroying medical waste directly at the point of its generation without forming environmentally hazardous residues and emissions.

Keywords: medical waste, incineration, plasma-chemical pyrolysis, military medical waste, plasma generator, mobile plasma arc unit

INTRODUCTION

As a result of the unrestrained growth and widespread use of disposable medical materials in the context of the Russian-Ukrainian war in Ukraine, the volume and rate of production of hazardous medical waste (HMW) are critically increasing. At the same time, today all medical waste in Ukraine is classified

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as hazardous, and the term 'medical waste' defines the full range of all categories and types of medical waste. According to the Order of the Ministry of Health of Ukraine of 8 June 8 2015 No 325 and other legal provisions/recommendations, medical waste in Ukraine is classified into four categories:
– A – epidemically safe medical waste,
– B – epidemically hazardous medical waste,
– C – toxicologically hazardous medical waste,
– D – radiologically hazardous medical waste.

At the same time, the current technological imperfection of the medical waste management system threatens human health and critically aggravates the environmental crisis.

The most common method of medical waste disposal in almost all countries of the world is incineration in the open air or in incinerators. However, due to the lack of modern high-performance and environmentally friendly technologies for the treatment and disposal of medical waste, up to 95% of medical waste ends up in authorised and unauthorised landfills and dumpsites, posing severe chemical, toxic, biomedical, carcinogenic, mutagenic, irritant, radiation, actively caustic, sensitising, flammable, explosive risks and many other health effects on Ukrainian citizens. At the same time, the improper handling of hazardous medical waste and its uncontrolled distribution can lead to infection of medical personnel and the public through skin, respiratory, and digestive tract infections.

The morphological composition of medical waste is unpredictable and depends heavily on the specifics and characteristics of the medical facilities that generate it, as well as on many other factors.

AIM AND METHODOLOGY

The purpose of this paper is to analyse the advantages and disadvantages of using high-temperature plasma--chemical pyrolysis for the disposal of hazardous medical and other wastes.

The following scientific methods were used for the analysis: comparison and generalization of statistical data on waste disposal in Ukraine in recent years. After such analysis, appropriate conclusions were drawn.

RESULTS OF THE STUDY

Analysis of the environmental hazards of the processes adopted in the updated medical waste management system in Ukraine

The process of open-air incineration of medical devices usually has a temperature of no higher than 500−700°C. Such low temperatures are insufficient for complete environmentally safe thermal utilisation and complete destruction of medical devices. This is because such low-temperature conditions produce new, equally dangerous, persistent chemical compounds – dioxins, furans, hydrochloric acid and other toxicants – that are released into the environment and further accumulate in food cycles.

The further combustion of such residues using additional chambers specially installed in incinerators often does not have the desired effect in terms of the norms and requirements of the current legislation of Ukraine, updated in accordance with European standards.

In view of this situation, the Ministry of Health of Ukraine, by its Order No 1602 of 2022, made important changes to the State Sanitary and Epidemiological Rules and Regulations on Medical Waste Management; changes aimed at reducing hazardous risks and blocking the pathways for hazardous substances and materials to enter household landfills/dumps.

The new regulations require all medical waste, except food waste, to be collected separately and then transferred for reuse and recycling.

Another important environmental innovation is the prohibition against chemically disinfecting infected hazardous medical devices, which eliminates the operation of dangerous soaking and rinsing of waste.

There is also a new provision requiring the appointment of specialists responsible for waste management in health care facilities (HCFs) who are obliged to develop standardised schemes for the management of medical waste, to regulate all actions in the management of medical waste in HCFs, from its generation to its disposal or transportation, and to be responsible for the implementation of these schemes.

However, the problem of providing modern technologies for the complete environmentally friendly and safe disposal of medical waste remains beyond the scope of the aforementioned Ukrainian Order No. 1602. In this case, special attention should be paid to the technological aspect of the disposal of waste from infectious and tuberculosis departments, veterinary waste and waste with biological weapons risks, as well as medical waste infected with dangerous diseases (AIDS, hepatitis, etc.). At the same time, despite the considerable cumbersomeness and overload of the medical waste management system, most methods and means of disinfection/disinfection of medical waste still require their additional final incineration with subsequent transportation of unburned ash residues to landfills and landfills. At the same time, the new technologies being introduced for the utilisation of medical waste until its complete environmentally safe destruction should fully cover the disposal of the entire range of hazardous medical waste produced by the more than 70,000 Ukrainian hospitals, clinics and other medical facilities and institutions.

Chemical disinfection/decontamination of various medical wastes before their official transfer to licensed companies for disposal also poses dangerous risks. In this case, there are additional environmental risks to the health of medical and transport personnel as a result of the joint synergistic effects of methylene blue disinfectant together with chemical disinfectants. To solve this problem, it is necessary to create new high--temperature technologies that can radically manage medical waste with fully guaranteed environmental protection during the restoration of community territories.

In Ukraine, relatively expensive incinerators have been used to incinerate hospital biological waste that, according to the World Health Organization (WHO), can dispose of hazardous medical waste in accordance with the most stringent requirements of the new European standards. It is believed that such incinerators can be operated within a radius of 50–100 m of hospitals or residential buildings.

For example, the French Muller S.R.50M incinerator (Fig. 1) for the incineration of organic solid waste completely destroys microorganisms and if any emission parameter exceeds the relevant European standard, the operation of the insinuator is automatically blocked. The incineration depth of infected medical waste reaches 95%, and the remaining 5% of the ash residue can be transported to a landfill. With an average specific heat of waste combustion of 3,500 kcal·kg^{-1} by high-temperature pyrolysis combustion at temperatures up to 850°C in the pyrolysis chamber, followed by afterburning of pyrolysis gases at 1,100–1,250°C in an additional chamber without the formation of 'black smoke' and fine dust, the productivity of Muller incinerators is 50–60 kg·h^{-1}.

The Muller S.R.50M incinerator destroys combustible medical waste, including epidemiologically hazardous waste, any combustible organic waste, hazardous biological waste from veterinary, livestock, poultry, meat processing, expired pharmaceuticals and pharmaceutical waste, radioactive waste and prohibited pesticides are excluded.

However, it should be noted that medical waste with such a caloric content is not common. At the same time, the Muller S.R.50M incinerator has rather bulky dimensions and high material consumption with its insignificant non-industrial capacity.

In addition, the principal technological temperature limitation of any incinerator is that to deepen the 'burnout' of environmentally hazardous substances newly formed in the combustion of medical waste, an additional amount of 'cold' air is required to be directed into the combustion chamber, which reduces the temperature in the combustion chamber to 400–500°C, which, among other things, does not ensure the guaranteed destruction of pathogenic extremophilic microorganisms.



Fig. 1. General view of the Muller S.R.50M incinerator made in France

Source: own photo.

The use of other non-combustion (non-fire) means, such as autoclaves and hydroclaves, for the sterilisation of waste by direct and indirect heating still requires further mandatory additional incineration in fire ovens of the medical waste treated in this way.

The same situation applies to very expensive microwave disinfection methods – medical waste sterilised by this method is also transported along with municipal waste to landfills or incinerated.

Against this background, plasma arc technology is the only technology capable of easily creating temperatures of up to 10,000°C and more in a medical waste combustion chamber. Commercially attractive technologies for the plasma-chemical pyrolysis of medical waste already exist and are easily scalable for both local and industrial scale utilisation, recycling and destruction of all types of medical waste without prior sorting. All these and other advantages make plasma-mode technologies unrivalled in terms of environmental safety when treating hazardous toxic waste, and, unlike their smoke-emitting counterparts, plasma-mode incineration and pyrolysis technologies destroy medical waste without the formation of environmentally hazardous residues.

The term 'plasma-chemical pyrolysis' defines the physicochemical process of decomposition of organic compounds carried out in low-temperature plasma with average molecular energies in the range of up to 50 eV. In this case, the plasma-chemical pyrolysis of hydrocarbons can take place directly in an electric arc (electro--cracking) or in a plasma jet of hydrogen and other gases.

Cooling/hardening of pyrolysis gas products with temperatures up to 3,700°C is most often carried out in heat exchangers. The products of the plasma-chemical process are also often cooled by water jets or jets of other liquid or gas coolants. At the same time, quenching of hydrocarbon plasma-chemical pyrolysis products with hydrocarbons increases the number of commercial products and improves the flexibility of regulating their chemical composition at lower energy costs. Therefore, the improvement of existing and development of new technological plasma-arc means of medical waste processing and utilisation is an extremely relevant practical scientific and technological problem. Compared to incinerators, plasma arc incineration maintains the temperature in the reactor's reaction zone at 1,200–3,000°C. At such temperature values in the reaction combustion zone, it is impossible for reactions to occur that result in the formation of highly toxic dioxins, phosgenes, polyhalogenated biphenyls or furans containing halogens (Paton, Cherenets, Marinsky, Korzhik & Petrov, 2005a, 2005b; Zhdanok & Mosse, 2008; Mosse, Savchenko, Savchyn & Levashov, 2012).

When plasma arc technology is used for medical waste disposal, the amount of toxic dioxins and furans is significantly less than the accepted emission standards and does not require sorting/separation of hazardous waste. At the same time, pathogenic microorganisms are completely destroyed.

Today, plasma arc technologies are environmentally acceptable industrial technologies that can create and maintain high temperatures of 1,100–1,300°C, high chemical reactivity and energy density for high-speed heat treatment, processing or disposal of medical and other solid, liquid and gaseous waste in milliseconds. In order to improve the economic and environmental performance for the plasma arc unit's own needs, it is possible to produce high-energy synthesis gas in the form of a mixture of carbon monoxide and hydrogen.

Consequently, the traditional incineration of medical, biomedical and chemical waste in the open air and in closed incinerators has dangerous environmental consequences over long periods of time. During long-term operation, the incinerators themselves become sources of environmentally hazardous pollution. Therefore, the development and creation of new economically and environmentally feasible technologies for the environmentally friendly and safe disposal of all types of medical waste has become a critical necessity. Today, many companies around the world, including Pyrolysis Systems Inc. (Canada), Siemens (Germany), Plasma Energy Applied Technology Inc. (USA), Plasmapole (France) and others, are developing high--temperature plasma arc systems for various purposes.

Global technological and environmental experience, and the current state of plasma technologies for medical waste disposal

Plasma is a mixture of neutral and high-energy charged particles with high kinetic energy. Ionised charged plasma particles are capable of entering into recombination reactions with detached electrons and in this process release significant energy in the form of ultraviolet radiation. The kinetic energy of the particles is converted into thermal energy, which is sufficient for the destruction of chemicals. Due to the presence of charged and excited particles in the plasma, the plasma environment becomes highly reactive and capable of catalysing homogeneous and heterogeneous chemical reactions.

In the case of plasma-chemical pyrolysis, solid medical waste containing carbon is gasified to form gas--aerosol mixtures that are subjected to cooling and purification. The purified mixture can be used to generate heat or electricity and to produce various fuels such as ethanol, hydrogen, and combustible synthesis gas in the form of a mixture of hydrogen and carbon monoxide. The inorganic materials are melted by plasma torches and separated in the form of a glassy, chemically resistant slag.

The significant heat generated in plasma-chemical reactors and combustible synthetic gases can be used in the plasma-pyrolysis cycle itself to save external energy resources, thus increasing the economic performance of the technology/plant. At the same time, the impact of plasma-chemical pyrolysis on the environment in terms of its environmental safety and its environmental manufacturability is superior to other methods and technologies for medical waste management.

Today, plasma arc heating technologies are already in use around the clock at various enterprises around the world. For example, six plasma torches with a total capacity of 2.5 MW are in constant operation at the Defiance plant in the United States to process more than 280 t of scrap metal per shift.

Historically, the first demonstration of a prototype electric arc incinerator in 1987 was carried out by Westinghouse Environmental Services in the United States. About a year later, in 1988, the Hungarian Institute of Electrical Industry developed a new pilot plasma reactor for the destruction of chemical waste (Krajcsovics, Pocsy, Emho & Puskas, 1988). A year later, in 1989, Retech Corporation of California and the U.S. Department of Energy initiated a joint program for the destruction of various wastes using plasma arc technologies (Cretenot, Vanrenterghem, Labrot & Pineau, 1990).

In 1994, the first rotary plasma furnace for the treatment of chlorinated organic compounds was created, with an organic contaminant destruction efficiency of up to 99.9% and very high dioxin and furan destruction characteristics at the level of $(5–9)\times10^{-3}$ ng·m^{-3}, which is much lower than the global environmental standards.

For many years, various companies around the world have been investigating plasma-arc treatment processes for many hundreds of different types of waste on an industrial scale. In this process, solid household and medical waste, ash, tires, coal and sludge waste, polychlorinated biphenyl, hazardous ash and sludge,

paints, solvents, various materials from landfills, as well as low-level radioactive waste, etc. have been effectively treated and utilised.

CSIRO/Siddons Ramset Ltd's PLASCON™, Retech, Westinghouse Plasma Company, Plasma Energy Corporation and other companies continue to develop large-scale plasma waste disposal systems.

In plasma-chemical pyrolysis processes, the main compounds formed from carbonaceous matter are methane, carbon monoxide, hydrogen, carbon dioxide, and water molecules. Plasma-chemical pyrolysis combines the thermochemical features of plasma with the process of pyrolysis using high-temperature plasma arcs in oxygen-deficient environments to completely degrade hazardous substances in waste into simpler molecules. At the same time, an important feature of plasma pyrolysis compared to the traditional incineration of solid combustible medical waste (CMW) is that preliminary sorting of chlorinated waste is greatly simplified or becomes unnecessary.

Compared to existing technologies, the thermal plasma treatment of medical and other waste has the following advantages:

1. At high temperatures, plasmo-chemical destruction reactions of hazardous molecules and heavily polluting molecular complexes occur, as well as melting with subsequent solidification and vitrification of the inorganic component of medical waste, which significantly reduces the volume of waste and hermetic coke pollution in the form of chemically resistant slag formations that are difficult to destroy.
2. The high energy density of 200 $GJ \cdot m^{-3}$ in the plasma torch makes it possible to create high-performance mobile and stationary installations with lower capital costs. The compact dimensions and high energy density significantly reduce the time to start up and shut down the plants.
3. The use of an electric arc as an energy source makes it possible to separate the heat generation process from the oxygen oxidation process, and it is independent of the oxidiser or air consumption. The use of high-temperature electric arcs also reduces the consumption of various plasma-forming gases.
4. The powerful ultraviolet radiation of the plasma arc significantly accelerates the destruction of waste, which is especially effective in the pyrolysis of organic chlorides. The high temperatures (Nema & Ganeshprasand, 2002) in the reaction zone minimise the duration of heat treatment of waste and achieve high productivity in its processing/recycling. Various automated means of monitoring and controlling the plant can be used for the highly efficient control of plasma-chemical processes.
5. The economic efficiency of plasmo-chemical means of processing various wastes can be increased by synthesising various commercial products with high added value for both external and internal needs.
6. The Plazmon-3 facility can completely destroy and utilise almost all categories of hospital waste: cotton products, various plastics, cellulose-polymer bandages, polyvinyl chloride blood bags, gloves and catheters made of polyurethane or silicone rubber, polyethylene and polymethyl methacrylate materials, glass and others, and as a result of exposure to powerful ultraviolet radiation, completely destroy pathogenic microorganisms, infected biomedical waste, and pathological waste and tissues. At the same time, medical waste is treated in the reactor without detailed sorting and without any segregation or pre-treatment.
7. The high-temperature plasma environment also completely destroys all types of bacteria, as evidenced by the results of bacterial tests for the presence of *Bacillus stearothermophilus* and *Bacillus subtilis* microorganisms in the smoke residues, which were specially grown in the laboratory on stainless steel strips and then passed through the high-temperature plasma environment in the primary chamber.

To organise a continuous plasma pyrolysis process, the temperature in the plasma chemical reactor should be maintained at 1,100–1,300°C. Moreover, each local volume of gas obtained in the process of waste processing should be in the specified temperature zone for less than or equal to 2 s (Vashchenko, Korduba, al Saeed Hafez, Nehoda & Tsybytovskyi, 2023). Under such temperature conditions, toxicants are completely decomposed, and the chlorine present in hydrochloric acid (HCl) easily forms salts in the purification processes.

To block the re-formation of toxicants, plasma pyrolysis products need to be cooled quickly. Especially intensively environmentally hazardous pyrolysis products are formed in the temperature range of 200–65°C with a maximum at a temperature of approximately 300°C. In order to bind chlorine into stable chemical compounds, the cooling process of plasma pyrolysis products is completed by passing them through a lime solution (milk of lime) or a soda solution (Zhovtianskyi et al., 2018).

Figure 2 shows a block diagram of the Plazmon-3 mobile plasma-chemical pyrolysis unit. It should be noted that this unit can also be used for the treatment of radio-pharmaceutical waste (Stockholm Convention on Persistent Organic Pollutants [SSCPOP], 2008).

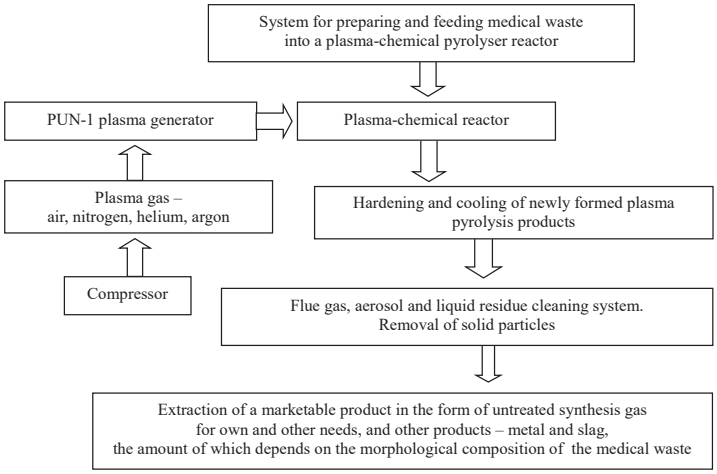


Fig. 2. Block diagram of the Plazmon-3 plasma arc pyrolysis unit with a capacity of 2–3 t·day^{-1} at a waste moisture content of –20%

Source: own work.

One of the main basic principles of the development and creation of mobile plasma plants is to ensure their maximum autonomy with the possibility of power supply from both stationary and autonomous mobile diesel generators. The Plazmon-3 mobile autonomous unit is fully assembled in a 20-foot sea container and can be transported to places of medical waste generation/accumulation.

The prototype of the Plazmon-3 unit was the experimental pilot Plazmon-1 unit (SSCPOP, 2008; Fig. 3). One of the main basic principles of the development and creation of mobile plasma plants is to ensure their maximum autonomy with the possibility of power supply from both stationary and autonomous mobile diesel generators. The Plazmon-3 mobile autonomous unit is, therefore, fully assembled in a 20-foot sea container and can be transported to places of medical waste generation/accumulation.

The main components of each plasma arc system are: plasma generator, power supply and cooling units for the plasma generator, plasma chemical reactor, compressor for supplying compressed plasma-forming gases to the plasma generator, system for preparing medical waste and feeding it to the reactor, cooling/hardening system for products generated in the process of plasma arc incineration of waste, system communication unit, control panel, unburned residue storage unit, final flue gas and aerosol products cleaning system, other auxiliary, control and management systems.

The Plazmon-1,2,3 experimental units were created based on a PUN-1 domestic direct-current plasma generator with air as the plasma gas. The PUN-1 plasma generator was developed at the E.O. Paton Institute of Electric Welding. The main tactical and technical characteristics of the Plazmon-3 unit are presented in Table 1.



Fig. 3. General view of the pilot experimental Plazmon-1 plasma arc unit

Source: own photo.

Table 1. Plazmon-3 specifications

Parameter	Unit	Value
Electric power of the PUN-1 plasma generator	kW	≤ 90
Temperature at the outlet of the plasma generator nozzle	°C	≤ 6 000
Temperature of the air jet into the reactive combustion zone (RCZ)	°C	≤ 1 500–3 500
Combustion temperature in RCZ depending on the composition and humidity of medical waste	°C	1 150–2 000
Plasma air velocity at the compressor outlet	$m \cdot s^{-1}$	50–90
Velocity of the air plasma jet at the inlet to the RCZ	$m \cdot s^{-1}$	20–100
Time of existence of pyrolysis products in the reactor before they start cooling	c	≤ 2
Degree of molecular destruction of waste	%	99.95
Temperature of the flue mixture at the outlet of the chimney	°C	76–90
Air consumption for cooling (quenching) of cool flame combustion products	m^3	≈ 150
Total amount of gases generated as a result of coalbed methane combustion that are supplied for cooling and cleaning	$m^3 \cdot h^{-1}$	≤ 1 000
Content of pollutants in the treated gas and aerosol flue residues emitted into the atmosphere	–	at the MAC level
Specific energy consumption	$kWh \cdot kg^{-1}$	1–2
Amount of heat generated from waste	$kWh \cdot kg^{-1}$ $kcal \cdot kg^{-1}$	1–2 1–3
Productivity at the entrance	$t \cdot day^{-1}$	2–3
Installation weight	kg	≤ 1 000
Installation dimensions	m	≤ 3 × 2 × 1.5

Source: own work.

The modular design of the plant makes it possible to arrange the plant for different process variants in order to adapt it to different types and categories of waste-solid, liquid, gas and aerosol, etc.

The technical documentation for the Plazmon-3 plant contains information on the structure of the medical waste disposal plant, the general principles of operation, operating and maintenance rules, as well as instructions for starting the plant and changing its operating modes. Compliance with the instructions, rules and regulations contained in this documentation ensures safe operation of the facility.

Mobile plasma arc pyrolysis unit

In recent years, due to the technological criticality of the situation with medical waste disposal in different countries, mobile plasma arc pyrolysis units have been of technological and environmental interest.

The layout of the technological flowchart, general view and design features of the Plazmon-3 mobile plasma pyrolysis unit for the disposal of medical waste, developed and manufactured in Ukraine, are shown in Figure 4 (Vashchenko et al., 2019).

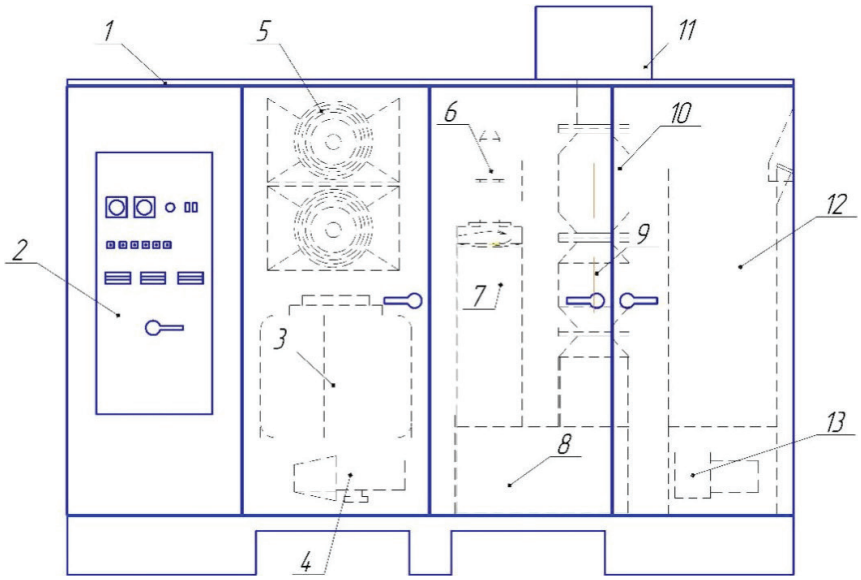


Fig. 4. Layout of the Plazmon-2 unit: *1* – frame-supporting structure; *2* – power unit and control panel; *3* – plasma generator cooling system tank; *4* – plasma generator cooling system circulation pump; *5* – plasma generator cooling system heat exchangers; *6* – plasma generator; *7* – high-temperature waste destruction reactor; *8* – container for collecting residual waste products; *9* – catalyst filter; *10* – muffler; *11* – finishing H14 high--temperature HEPA filter, *12* – temperature sensor, *13* – level sensor

Source: Vashchenko et al. (2019).

The experience gained in the development and creation of the Plazmon-1,2,3 prototype global experimental and industrial plasma arc installations shows their high efficiency in the use and destruction of various medical wastes of any category.

The plasma-chemical pyrolysis technology eliminates almost all the disadvantages of other currently available medical waste disposal technologies and is a comprehensive solution for their safe disposal with a conversion of organic matter into gas of more than 99% and does not require the segregation of chlorinated

hydrocarbons. After the waste is incinerated, toxic gases are present in a very small amount at the outlet of the plant, in accordance with regulatory environmental requirements. At the same time, the high temperature and UV radiation of the plasma jet completely destroy bacteria/microorganisms. Therefore, plasma technology can greatly simplify many of the numerous processes of medical waste management.

CONCLUSIONS

1. Electric arc plasma-chemical pyrolysis meets all the technical requirements for the treatment of hazardous medical waste and is easy to maintain in the reactor's reactive oxygen-free environment. It is also possible to change the plasma-forming gas and, thereby, to change the chemical characteristics of the processes taking place in the reactive environment of the plasma-arc reactor.
2. The synthesis gas obtained through plasma arc pyrolysis can be burned for the plant's own needs in its reaction zone, saving electricity from external sources.
3. The results of a comparative analysis of the currently available technologies for the disposal of municipal, medical and other industrial wastes demonstrate the advantages of plasma-arc pyrolysis while also making it uncompetitive for the disposal of hazardous toxic waste. Unlike smoke analogues, its emissions of toxic dioxins and furans into the environment are significantly lower than the accepted standards, and do not require the separation of hazardous waste. At the same time, pathogenic microorganisms are completely destroyed.
4. It would be expedient and profitable to develop and manufacture autonomous mobile modular plasma pyrolysis plants with a capacity of 50–100 kW based on domestic PUN-1 plasma generators with optimal gas consumption for plasma formation. At the same time, the air consumption is 2–15 $m^3 \cdot h^{-1}$, with a minimum consumption of industrial water for cooling the plasma generator in the range of 150–200 $g \cdot s^{-1}$ at an efficiency of up to 70%, and at an optimum temperature of the plasma jet at the outlet of the plasma torch nozzle in the range of 4,300–5,000°C, which is confirmed by experimental measurements.
5. The productivity of the Plazmon-3 unit is 0.5–1.0 $t \cdot MW \cdot h^{-1}$, depending on the composition of the waste and its moisture content, the morphological and physicochemical composition of which has unpredictable seasonal changes, and the nature and purpose of the sources of its generation. The mobility of the facilities makes it possible to destroy medical waste at its place of generation or accumulation, which largely eliminates the need for detailed waste sorting, drying and transportation.

Authors' contributions

Conceptualisation: V.V., I.K. and S.T.; methodology: N.M., Y.T. and N.N.; software: S.T.; validation: V.V. and I.K.; formal analysis: V.V.; investigation: I.K., N.M. and N.N.; resources: Y.T.; data curation: S.T., Y.T. and I.K.; writing – original draft preparation: V.V. and N.M.; writing – review and editing: Y.T.; visualisation: S.T., N.N. and N.M.; supervision: Y.T.; project administration: V.V. and I.K.; funding acquisition: I.K. and S.T.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Council Decision 93/98/EEC of 1 February 1993 on the conclusion, on behalf of the Community, of the Convention on the control of transboundary movements of hazardous wastes and their disposal (Basel Convention) (OJ L 39, 16.2.1993, pp. 1–2).

Cretenot, D., Vanrenterghem, J., Labrot, M. & Pineau, D. (1990). *Waste destruction by plasma*. EPRI Symposium on Industrial and Environmental Applications of Plasma, Palo Alto, California, March 7–9.

Krajcsovics, F., Pocsy, F., Emho, L. & Puskas, Z. (1988). In R. Abbou (Ed.), *Hazardous Waste: Detection, Control, Treatment* (pp. 1609–1614). Amsterdam: Elsevier.

Mosse, A. L., Savchenko, G. E., Savchyn, V. V. & Levashov, A. V. (2012). Mobile plasma systems. Variants of execution, use and comparative analysis. *Energy Technologies and Resource Saving*, *4*, 8–15.

Nakaz Ministerstva Okhorony Zdorovya Ukrayiny vid 06.09.2022 No 1602'Pro zatverdzhennya Zmin do Derzhavnykh sanitarno-protyepidemichnykh pravyl i norm shchodo povodzhennya z medychnymy vidkhodamy' [Order of the Ministry of Health of Ukraine of 6 June 2022 No 1602 'On approval of amendments to the state sanitary and anti-epidemic rules and regulations on medical waste management']. Vidomosti Verkhovnoyi Rady Ukrayiny (VVR) No 1602 of 08.11.2022, VVR, No 1387/38723.

Nakaz Ministerstva Okhorony Zdorovya Ukrayiny vid 08.06.2015 No 325 'Pro zatverdzhennya Derzhavnykh sanitarno--protyepidemichnykh pravyl i norm shchodo povodzhennya z medychnymy vidkhodamy' [Order of the Ministry of Health of Ukraine of 8 June 2015 No 325 'About approval of the State sanitary and anti-epidemic rules a regulations according to the address with medical waste']. Vidomosti Verkhovnoyi Rady Ukrayiny (VVR) No 325 of 07.08.2015, VVR, No 959/27404.

Nema, S. K. & Ganeshprasand, K. S. (2002). Plasma pyrolysis of medical waste. *Current Science*, *83* (3), 271–278.

Paton, B. E., Cherenets, A. V., Marinsky, G. S., Korzhik, V. N. & Petrov, S. V. (2005a). Prospects of application of plasma technologies for destruction and processing of medical and other hazardous waste. Part I. *Modern Electrometallurgy*, *3*, 54–63.

Paton, B. E., Cherenets, A. V., Marinsky, G. S., Korzhik, V. N. & Petrov, S. V. (2005b). Prospects of application of plasma technologies for destruction and processing of medical and other hazardous waste. Part II. *Modern Electrometallurgy*, *4*, 52–60.

Stockholm Convention on Persistent Organic Pollutants [SSCPOP] (2008). *Guidelines for best available techniques and preliminary guidance for best environmental practices relevant to Article 5 and Annex C of the Stockholm Convention on Persistent Organic Pollutants*. Geneva: UNEP.

Vashchenko, V. M., Antonov, A. V., Loza, E. A., Korduba, I. B. & Kapusta, T. Y. (2019). Prospects for the introduction of plasma technology for hazardous waste treatment. In *Proceedings of the XIII International Scientific and Technical Conference "Problems of Ecology and Energy Saving"*. Mykolaiv, Ukraine, September 20–22 (pp. 119–120).

Vashchenko, V. M., Korduba, I., Saeed Hafez, N. M. al, Nehoda, N. & Tsybytovskyi, S. (2023). *Utility model patent No. 154899. Installation for plasma destruction of waste. Issued in accordance with the Law of Ukraine "On Protection of Rights to Inventions and Utility Models"*. Registered in the State Register of Utility Models of Ukraine on 27.12.2023

Zhdanok, S. A. & Mosse, A. L. (2008). Plasma Methods for Toxic Wastes Processing. In S. Güçeri, A. Fridman, K. Gibson, C. Haas, C. (Eds), *Plasma Assisted Decontamination of Biological and Chemical Agents* (pp. 143–149). Dordrecht: Springer.

Zhovtiansky, V. A., Petrov, S. V., Orlyk, V. M., Yakymovych, M. V., Vakilov, I. M., Nazarenko, V. G, Vabishchevych, M. S., Voloshyniuk, I. M. & Yakubyshyn, Y. A. (2018). Recycling of hazardous and radioactive waste using plasma technologies. *Ecological Sciences*, *2* (21), 49–58.

PODSTAWY INŻYNIERYJNE I FIZYCZNE ORAZ BEZPIECZEŃSTWO ŚRODOWISKOWE UTYLIZACJI PLAZMOWO-CHEMICZNEJ NIEBEZPIECZNYCH ODPADÓW MEDYCZNYCH

STRESZCZENIE

Nieograniczony wzrost ilości i tempa produkcji niebezpiecznych odpadów medycznych w kontekście wojny rosyjsko-ukraińskiej krytycznie pogarsza sytuację środowiskową na Ukrainie. Jednocześnie istniejące tradycyjne metody i środki technologiczne nie są w stanie zapewnić ich całkowicie bezpiecznego dla środowiska przetwarzania i usuwania. W artykule rozważono alternatywną technologię wysokotemperaturową do pirolizy plazmowo-chemicznej odpadów medycznych w temperaturze 1100−1250°C, która jest realizowana w postaci mobilnego urządzenia do pirolizy plazmowej Plazmon-3, zaprojektowanego i zbudowanego według wzoru krajowego uniwersalnego generatora plazmowego

PUN-1. W artykule opisano również konstrukcję, zasadę działania, inżynierię i zasady fizyczne leżące u podstaw zbudowania urządzenia Plazmon-3, przeznaczonego do utylizacji dowolnego rodzaju i kategorii odpadów medycznych poprzez ich zniszczenie wskutek działania palnika plazmowego o wysokiej temperaturze prądu stałego generowanego przez generator plazmowy PUN-1. Opisano także główne cechy operacyjne urządzenia Plazmon-3. Jako gazy plazmotwórcze w instalacji można stosować powietrze, azot, argon, hel i inne gazy. W artykule opisano zalety stosowania wysokotemperaturowej pirolizy plazmowo-chemicznej do utylizacji niebezpiecznych odpadów medycznych i innych, które sprawiają, że technologia ta pod względem bezpieczeństwa dla środowiska naturalnego przewyższa konkurencję i w przeciwieństwie do swoich odpowiedników emitujących dym jest w stanie niszczyć odpady medyczne bezpośrednio w miejscu ich wytwarzania, bez tworzenia niebezpiecznych pozostałości i emisji.

Słowa kluczowe: odpady medyczne, spalanie, piroliza plazmowo-chemiczna, wojskowe odpady medyczne, generator plazmy, mobilna jednostka łuku plazmowego

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ORIGINAL PAPER

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ANALYSIS OF THE IMPACT OF THE GLOBAL CRISIS IN 2021–2024 ON THE DEVELOPMENT TIME OF MULTIFAMILY BLOCKS

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ABSTRACT

The study describes the timeline of a construction project comprising six residential buildings, green spaces, and a playground. The project was carried out in the Warsaw area between 2022 and 2024. The investment was undertaken following significant events such as the COVID-19 pandemic, rising inflation, and the armed conflict in Ukraine. The study focuses on the analysis of selected phases of construction work performed as part of the investment described. The specific tasks highlighted include the installation of window joinery, the construction of internal masonry walls, the installation of partitions and balcony railings, as well as the delivery and installation of lifts. Additionally, general data on the work progress, construction schedule, and entries from the construction logbook referring to the specific completion dates of various stages were examined. Based on the provided data, an analysis was conducted to compare the time required to complete individual construction tasks against the schedule established during the project planning phase. The text addresses the challenges of meeting deadlines in large construction projects, where the technology used, the number of personnel employed, and the scale of the investment contribute to the extension of the construction process by the contractor.

Keywords: schedule, project completion time, investment process, global crisis, multifamily housing construction

INTRODUCTION

The period between 2020 and 2023 presented Poland with a series of significant challenges, with a notable impact on the economic sector and the residential property market. The primary factors that contributed to the deterioration of the economic situation in Poland were consequences of the global pandemic caused by the SARS-CoV-2 virus (COVID-19), and the ongoing armed conflict in Ukraine. The pandemic led to a significant disruption of cities, negatively affecting areas such as employment, property sales, the emergence of new investments, and the expansion of existing ones. In order to stop the spread of the virus, governments around the world introduced a number of restrictions that affected business and social activity. Many people lost employment, which contributed to a decline in housing sales, but also an increase in the collection of loans and credit (Karpio, Wielechowski & Woźniakowski, 2020; Kaźmierczak, 2021; Łaszek, Olszewski & Augustyniak, 2024). Additionally, the Polish government implemented measures to restrict the spread of the virus, which contributed to the overall decline in the country's economic activity. The first wave of restrictions came into

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force in March 2020, which included bans on gatherings, closed public places such as shopping centres, gyms, hairdressers and beauty salons, suspended the activities of nurseries, kindergartens and schools, and prohibited people from city beaches and green areas. More stringent restrictions came into force in May 2020. The holiday period passed quietly, but the autumn of 2020 again brought more COVID-19 cases, prompting the authorities to re-implement the strict restrictions (Związek Przedsiębiorców i Pracodawców [ZPP], 2021; Markowska & Strahl, 2022). A significant number of construction sites experienced delays or complete stoppage of work due to a shortage of manual and office-based personnel. Some of the existing staff were in home quarantine or hospitalised, which created obstacles to work. Consequently, some investments came to a standstill and the entire implementation plan was delayed. Another reason for the stoppage of construction work was the difficult transport of materials. Orders were shipped late or transported in parts, due to shortages in crews, restrictions due to the need to quarantine shipments, or difficulties in communication with the logistics company (Dutka, Stołecka & Janiak, 2021). The restrictions were upheld until 17 January 2021. Further restrictions, lockdowns and closed plants would have led to even greater losses, resulting in fears of a complete economic collapse. Restrictions also applied to the number of workers on the job and included the maximum number of people based on the work area (ZPP, 2021; Kłosowska, 2022; Kraska & Kot, 2024; Marecik, 2024). This caused another staffing problem in the execution of large investments, where many works could not be carried out simultaneously.

All the constraints and staff shortages affected the execution time of the investments, which were delayed in relation to the original assumptions and schedules. The restrictions on the functioning of the economy had numerous negative consequences, both globally and for the Polish economy. In the second quarter of 2020, the European Union's gross domestic product (EU GDP) fell by 13.9%; in Poland, the decline was 8% and unemployment rose by 2.7%. These were the steepest declines since the measurements in 1995 (Liu, 2020; Kaźmierczak, 2021; ZPP, 2021). In Poland, the change observed in the level of inflation was influenced by multiple factors, extending beyond the direct impacts of the ongoing pandemic. These include both internal developments and external events occurring beyond the country's borders. These included the war in Ukraine, the migration of people, and an increase in lending rates. There was an increase in inflation and housing and rental prices. However, when interest rates were raised, demand fell, which resulted in stagnation in the construction sector and the housing sales market. Purchasing a house or flat became unattainable for many people, resulting in an increase in demand for residential rental properties. However, the cost of renting flats at that time was lower than the cost of paying the mortgage needed to buy a flat or house (Węgrzyn & Topczewska, 2023; Kraska & Kot, 2024; Łaszek et al., 2024). In the first half of 2020, there was a sharp decline in interest in loans due to the current credit market situation, but the second half of the year saw an increase.

This was a result of the lack of a stable financial situation for many companies, which prompted a significant part of the population to take out loans. In response to the growing credit risk, the requirements for borrowers were tightened. As a result of lower lending rates and negative interest rates, the loan portfolio increased by 0.9 billion PLN in June 2021. In the first quarter of 2021, there was a change in the terms and conditions of loan intake. The own contribution was reduced, but loan margins for borrowers were raised. The third quarter of 2021 saw strong demand driven mainly by demand for the purchase of durable goods and an improvement in the economic situation in the country (Czajkowska, 2021). By the first quarter of 2022, inflation had reached its highest level in the 21st century. In May 2022, inflation was at 13.9%. At the end of 2021, the National Bank of Poland (*Narodowy Bank Polski*) started to raise interest rates, but inflation continued to rise. The rapid rise of inflation contributed to an increase in lending rates. This situation affected borrowers who had taken out a loan when interest rates were close to zero. This condition persisted throughout 2022 and early 2023 (Marcinkowska, 2022; Węgrzyn & Topczewska, 2023; Kraska & Kot, 2024; Łaszek et al., 2024).

The war on the Ukrainian territories, which began in February 2022, caused a significant influx of Ukrainian refugees into Poland, especially women with children, which resulted in them needing to find new locations to live. The increased cost of renting flats and houses prompted the Polish government to introduce additional financial support schemes for Ukrainian refugees. The war forced many small business owners to flee Ukraine, which contributed to an increase in demand for housing and commercial premises, as they had to find new locations to run their businesses on Polish soil. The situation was also exacerbated by an increase in the price of construction materials from Ukraine and Russia; shipments to Poland were restricted, and some even stopped. This put additional strain on the construction market in Poland and the search for new suppliers began, which proved to be a difficult undertaking to carry out in a short period of time. As a result, delivery and construction times were extended (Sosna, 2022; Kałuża-Kopias, 2023; Węgrzyn & Topczewska, 2023; Łaszek et al., 2024).

Transporting material to the construction site is a complex process. It is often the case that an order passes through several suppliers, as a result of which the delivery time may be extended. When large-volume deliveries are involved, the timing of the transport must also be considered so that the delivery is as fast as possible and does not create traffic problems for other road users (Szruba, 2021; ZPP, 2021).

In the years 2021–2024 described, transport was hampered by lockdowns, quarantines, staff shortages, and shortages in material deliveries from Ukraine and Russia. Working hours on site were prolonged because material deliveries were extended. As a result, subsequent construction work was delayed, resulting in increases in the overall project duration (Czapla, 2020; Sosna, 2022). Construction is an important branch of the Polish economy, which also has a significant impact on other industries. Figure 1 shown all the links of the construction industry with other industries. When the development of the construction sector is stunted, other industries are impacted, and as a result, the development of the country's economy is also affected.

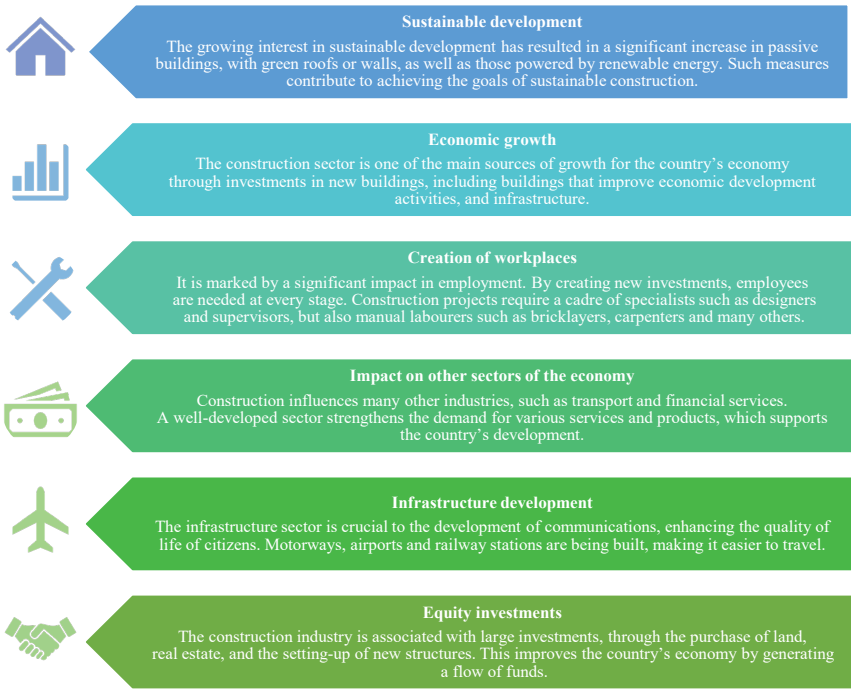


Fig. 1. Impact of the economic sector on construction

Source: own work based on Adamczak-Bugno (2023).

In the construction sector, inflation has been high for several years, both for construction works and the prices of materials, including raw materials. Industry fluctuations are due to the low number of new businesses, but also to price volatility and staffing (Kaźmierczak, 2021; Markowska & Strahl, 2022; Adamczak-Bugno, 2023).

In the construction industry, strategic materials such as cement, concrete and aggregate can be distinguished. The listed materials are the main components needed to create, among other things, concrete mix. According to the Polish Association of Construction Industry Employers (*Polski Związek Pracodawców Budownictwa*), phenomena such as problems in obtaining components for production, production, or disrupted logistics through COVID-19 and the military action in Ukraine have contributed to the rise in prices of strategic products (Polski Związek Pracodawców Budownictwa [PZPB], 2023).

Figure 2 shows the four most important strategic materials in the construction sector, without which the work on a construction site could not take place. These are cement, concrete, aggregates-mixes and aggregates-grits. It is with these intermediate products that mixes are manufactured, such as reinforced concrete or reinforced cement, mortar, and the proper mix for pouring floors.

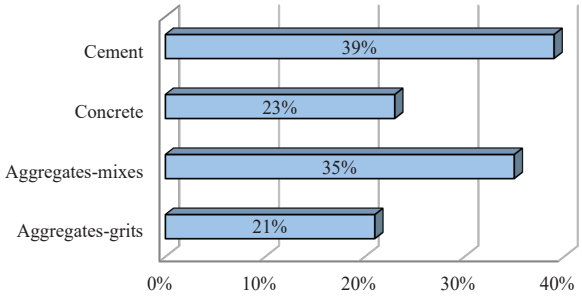


Fig. 2. Increase in the price of strategic materials

Source: own work based on PZPB (2023).

In the construction sector, the main drivers of the industry are employment and wages. Construction is a sector that creates many jobs for skilled workers as well as beginners without significant experience. Wages depend on the skills and training of the worker. The rate is also influenced by aspects such as the advancement of the work, complexity, size and location of the project. According to Statistics Poland (*Główny Urząd Statystyczny*) data, the average employment in September 2023 was 6.5 million full-time equivalents (FTEs), while the average salary in September was 7,379.88 PLN gross. There was an increase in all Polish Classification of Activities (PKD) sections. For the construction industry, it amounted to 6.9% (Adamczak-Bugno, 2023). 'Based on the *Global Powers of Construction (GPoC) 2022* report prepared by Deloitte, the total cash inflow of the top 100 global companies in 2022 amounted 1.94 trillion USD. Total revenue increased by 6.3% year-on-year, but capitalisation decreased by 14.9% to 598,577 million USD [own translation]' (Adamczak-Bugno, 2023, p. 23). Similar statistics have been presented in Poland by Statistics Poland and concern, among other things, price indices for selected construction works over the period 2021–2023, reflecting the dynamic situation of construction and assembly production prices. By analysing the statements available on Statistics Poland's website, for multifamily buildings of five- and six-storeys, which according to statistics belong to the category of buildings of collective residence, one can notice an increase of approximately 2–7% of the prices of finishing works. The statements presented here concern the prices of masonry structures, building brick partitions, window joinery, scaffolding, as well as aluminium structures and interior furnishings.

The data in Table 1 shows a comparison of the percentage increase for December in selected years, where prices in the previous months of the given year are set at 100%. Masonry construction or brick partitions cost the most in 2022. In 2023, there was a decrease of 7% and 9%, respectively. Carpentry saw the largest price increase for 2022, with a rise of just under 12% compared to 2021 and 2023. The biggest increase in 2023 was for scaffolding, which registered a jump of 5.4% compared to 2022.

Table 1. Price indices of construction objects in 2021–2023

Specification	21st of December	22nd of December	23rd of December
		%[a]	
Masonry structures	6.5	12.5	5.3
Partition walls made of building bricks	6.7	14.5	5.7
Construction joinery	8.2	20.6	8.2
Scaffoldings	4.5	9.0	14.4
Aluminium constructions and interior furnishings	8.9	25.3	9.9

[a]100% previous month of the year.

Source: own work based on Statistics Poland.

Figure 3 presents the price indices of construction objects in 2020–2024. It shows changes in the years of the pandemic and the war in Ukraine. The analysis of building price indices conducted by Statistics Poland for many years shows significant price fluctuations between 2022 and 2024, characterised by both drastic decreases and increases. Figure 3 illustrates price fluctuations between 2020 and 2023. As can be seen, the largest percentage index was recorded in 2022, reaching almost 16%. In contrast, the smallest percentage index for building prices, just over 2%, was recorded in 2020. That year, the economy was going through

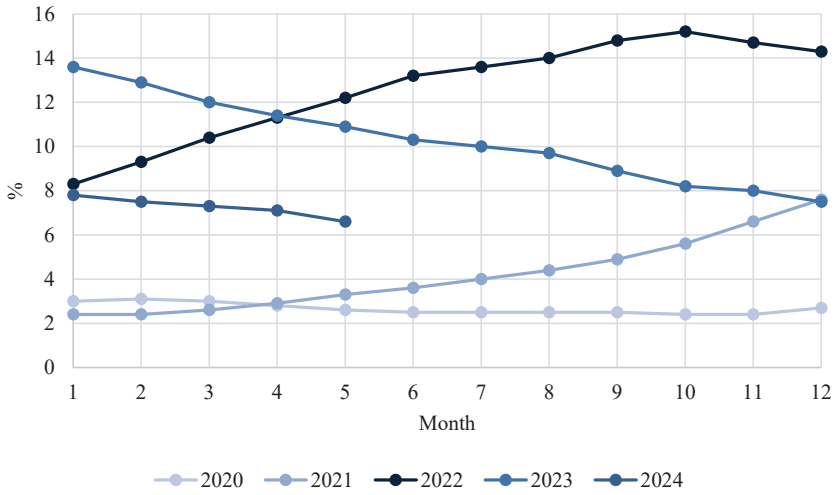


Fig. 3. Price indices of construction objects in 2020–2024

Source: own work based on Statistics Poland.

a very difficult time; the COVID-19 pandemic started, which slowed down the economic development as a result of the lockdowns. In contrast, 2022 was a time of economic recovery for the country. Considering both domestic and global events, an increase in prices was observed from 8% to 15%. In 2023, a decrease was observed from 14% to around 7%. For April 2022 and 2023, the value was the same, at around 11%. The first quarter of 2024 did not bring a sharp change, rolling along at an even level compared to the third quarter of 2023 (Fig. 3). Considering all the described aspects and situations in the country, it can be deduced that the statistics published by Statistics Poland for 2023 in the first quarter and second quarter brought a decrease in the prices of materials and construction works, resulting in increased activity in construction and assembly production. The current value for 2024 is observed to decrease at 7–8%.

An equally important aspect besides pricing in the implementation of a construction project is timing. In order to create a good work schedule, all possible factors that may occur during the project must be considered.

The project timescale defines a range of dates for the construction work divided into appropriate stages. However, it is made up of what are known as sub-stages: placing the formwork, creating and placing the reinforcement, and only the final stage is concreting the previously prepared base for the floor in question (Siewiera, 2018; Kłosowska, 2022; Sitek, 2022).

The investment process is a complex time consisting of many interrelated stages, as each investment is independent and unique and therefore needs an individual approach to developing its implementation plan. Each of the four stages of the investment process illustrated in Figure 4 discusses the entire construction process from start to finish, covering the most important aspects during the planning of the investment, the creation of the investment and the handover of the finished product to the client. More information about each of these stages can be found in Figure 4.

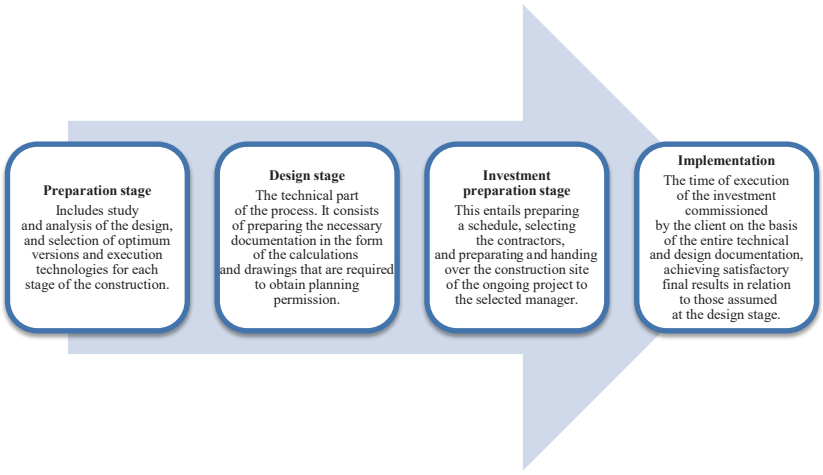


Fig. 4. Stages of the investment process

Source: own work based on Sitek (2022).

Time is an important factor that determines productivity. Inefficiencies in construction processes and unplanned expenses can prolong the construction time and increase its cost. The chosen technology and materials determine how long the construction will take. Nowadays, there are many options, with finances being the only limitation. Innovative solutions and creative approaches by engineers on site can

effectively reduce the execution time of an investment (Siewiera, 2018; Dutka et al., 2021; Sitek, 2022). Over the past 10 years, the construction industry has seen the emergence of many innovative solutions that increase productivity and efficiency. The COVID-19 pandemic is a factor that accelerated development specifically in the field of innovative approaches in construction, as it forced entrepreneurs to change the way they operate. The available software and mobile solutions significantly help manage the investment at every stage – from design to construction to facilities management. Construction companies are taking advantage of the new technologies available on the domestic market to improve productivity, communication between contractors and even decision-making between trades. In the past three years, only a quarter of construction projects have been completed within the original deadlines (Kaźmierczak, 2021; Sitek, 2022).

Non-productive activities such as researching project information, resolving controversies or finding errors and reworking them take up around 35% of a construction worker's time, which equates to 14 h per week. Therefore, new technologies, the use of cloud or building information modelling (BIM) software streamlines their work and allows them to find solutions to conflicts between different trades within a project (Sitek, 2022).

Aspects such as the technology and timing of prefabricated balconies, the installation of window joinery, the installation of lifts and internal masonry works in the selected buildings were considered in the analysis. The choice of specific works was motivated by the fact that the selected works were carried out between 2022 and 2024, i.e. during the crisis caused by the COVID-19 pandemic and the armed conflict in Ukraine. All the works described need teamwork, long lead times, and worker-engineer cooperation, and their execution time depends on availability and supply in both the domestic and international markets. The specified works also give an individual architectural character to the buildings. The stages of execution of these works are different, as each is carried out at different points in the overall construction process. The selected elements are part of the construction process, through which we achieve the raw closed state of the investment.

The aim of the study was to analyse the impact of the external factors discussed earlier on the execution time of a multifamily apartment block investment in Warsaw in the timeframe 2022–2024. All considerations will focus on selected aspects of the execution of the construction on six buildings with five or six storeys, founded on two garage slabs. The analysis was conducted as a comparison of the investment's execution schedule to the construction logbook, which is systematically kept in accordance with the Act of 7 July 1994, known as the Construction Law (Journal of Laws of 1994 nr 89, item 414).

Works such as the installation of lifts, installation of window frames, construction and installation of prefabricated balconies, and internal masonry works in the selected two buildings will be considered. The data were interpreted using graphs created in Microsoft Excel, R (programming language), and via the creation of a summary of the results in illustrative and descriptive form, considering the current situation in the construction market between 2020 and 2024. Events that significantly affected the performance of the described investment were mainly the COVID-19 pandemic and the war in Ukraine. Last but not least, there were staff shortages and logistical problems in the then unstable domestic market. The article considers such aspects, which could have significantly influenced the time of delivery of the investment to the contracting authority. The above-mentioned aspects were considered when analysing the execution time of the investment of six multifamily blocks of flats in Warsaw.

MATERIAL AND METHODS

The development being analysed was built between 2021 and 2024. It consists of six independent residential buildings with a total of 316 flats, situated on two garage slabs with a total of 220 parking spaces in garage slab G1 under buildings numbered B1, B2 and B3, and 232 parking spaces in garage slab G2 under buildings

numbered B4, B5 and B6. Figure 5, designed following the provisions of the local development plan, shows all the main elements of the development construction project. Figure 5 shows a bird's-eye view of the site area, including the buildings with their entrance staircases, garage access roads, pavements and landscaping. The green roofs on buildings B1, B2 and B4 are also shown.



Fig. 5. Site development plan of the described investment

Source: Authorship – PIG Architects.

A technology that indicates the investment's connection with nature is the use of green roofs on buildings B1, B2 and B4. Sedum matting was used to achieve this effect. The use of such a solution on the roofs of the buildings provides an additional biologically active area and a harmonious visual result to the entire structure.

Table 2 summarised the buildings, the number of storeys above ground, the number of dwellings in each building and the commercial premises. The number of parking spaces on each of the two garage levels and the location of the garage levels under the buildings are also shown in the table. Labels following the pattern B1 mean building number 1, etc., while G1 refers to garage slab number 1.

Table 2. Summary of the number of flats in each building

Building	Number of floors above ground	Number of apartments	Commercial premises
B1	5	33	–
B2	5	40	–
B3	6	76	10
B4	5+ mezzanine	54	–
B5	6	75	9
B6	6	38	4
G1	under B1, B2, B3	220 parking spaces	–
G2	under B4, B5, B6	232 parking spaces	–

Source: own work based on construction data.

Table 3 shows a breakdown of the different areas for the investments described. The data shown in the table comes from the construction log. The area in question is equipped with many innovative and environmentally friendly system solutions. One of these is the retention and drainage systems designed to drain rainwater. This solution was applied because the area where the project is located has a low groundwater table. Also, the area is flat and located in the Vistula wetlands.

Table 3. Balance of the development area of the described project

Specification	Land balance		
	size	coefficient	local development plan
Site area	18,926.05 m^2	–	–
Building surface area	5,103.2 m^2	–	–
Hard surfaced area	3,431.5 m^2	–	–
Biologically active area on native ground	4,318.2 m^2	–	–
Biologically active area on garage floors and roofs	3,273.9 m^2	–	–
Total biologically active surface area	7,592.1 m^2	0.4011	min. 0.40
Total surface area (aboveground)	28,322.48 m^2	–	–
Total surface area (underground)	12,426.48 m^2	–	–
Intensity		1.496	max. 1.5
Height	max. 19 m	–	max. 19 m
Number of floors	5–6	–	–
Number of parking spaces for flats	452 (garage) + 25 (land)	–	1.5 parking spaces per location
Number of parking spaces for services	30 (land)	–	30 per 1,000 m^2

Source: own work based on construction data.

An analysis of Table 3 shows that the height of the blocks is up to 19 m in accordance with the local development plan (LDP). The development intensity factor is 1.496. The land balance shows that the total area of the aboveground part of the development is 28,322.48 m^2, and the underground part is 12,426.48 m^2.

The entire area is fenced off, making it a separate estate. The internal area is equipped with small architectural features such as benches, children's playgrounds, an outdoor gym complex and bicycle repair stands. The area has many green zones, with numerous plantings of flowers, shrubs and low trees. The biologically active area is 7,592.1 m^2, which gives a coefficient of 0.4011, in accordance with the LDP. All the important figures for the investment in question can be found in Table 3.

The space is dotted with numerous paths leading to the entrance cages of the blocks, as well as to landmarks throughout the square. As a whole, it is an intimate neighbourhood ideal for families with children, seniors, as well as young people.

A timesaving technology used in the construction of the multifamily blocks of flats is prefabricated balconies. Prefabricated balconies are prefabricated building elements that are manufactured in factories, then transported to the construction site and assembled using special balcony connectors. The balcony connectors are designed in such a way that all vertical and horizontal forces are transferred directly to the floor slab. These balcony connectors are made with innovative technology that ensures easy installation and reliable load transfer (Halfen, 2020).

The use of this solution helps to reduce the construction time, as the balconies are ordered much earlier so that they arrive on site in good time. The whole process of making the balconies is economical; we do not need several workers to make one monolithic balcony, because all the work of these people is done by a precise machine controlled by a specialist. The whole technology optimises the time of creation, delivery and installation (Halfen, 2020; Yang, 2023).

Masonry walls are an important part of the whole building, dividing the internal space of the building into smaller rooms and acting as sound insulation. The construction of partition walls is carried out in several stages, which can be divided into preparation, bricklaying, and finishing. The first involves preparing the surface, marking out the course of the wall. In the next stage, we lay the masonry components while controlling for the level and straightness. The final stage is filling the joints with mortar and smoothing the surface. This wall is then prepared for further finishing works (Rodrigues & Šipoš, 2019; Wang et al., 2023).

The vertical partitions consist of several layers, arranged in such a way as to provide adequate acoustic, thermal, and comfort conditions. Several types of internal masonry walls can be distinguished in the developments described. Each has thermal insulation, a load-bearing and insulating part and a plaster layer. The main part of the wall structure is made of 8–18-centimetre-thick silicates. For example, a 12-centimetre wall element, used as a partition between a utility room and a bathroom. Figure 6 shows a cross-section of the wall described.

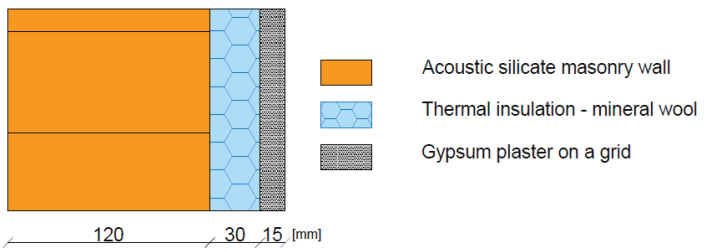


Fig. 6. Site development plan of the described investment

Source: Authorship – PIG Architects.

In residential building, windows provide thermal, acoustic and aesthetic comfort. In the project described, PVC (polyvinyl chloride) and aluminium joinery were installed. There were three types of glazing: standard, and glazing with a total solar factor *g*0.35 and *g*0.27. Such glazing was used in premises where the sun shines for most of the day. This provides a comfortable living environment in every room, without the need for additional sunshades. Window acoustics is a property that is currently gaining importance. It is considered an essential feature of glazing due to the location of multifamily buildings in city centres, along busy streets or near industrial plants. Taking all these elements into account, we have to define the right parameters for the designed dwellings in order to ensure appropriate indoor conditions (Nurzyński, 2002). This enables us to meet the relevant sound insulation conditions in accordance with the product standard PN-EN 14351-1:2006+A2:2016 (Polski Komitet Normalizacyjny [PKN], 2016). In the investment described here, warm-mount aluminium frames were also used for the shop windows of the ground floor commercial premises in buildings B3, B5 and B6. This solution provides a pleasant view into the interior of the premises. Figure 7 shows a cross-section of the north elevation of the B3 building as an example of all buildings in the investment. This picture shows details of each element of the external part of the building, which represents the whole project designed by the architecture group.



Fig. 7. Cross-section of the north elevation of building B3

Source: Authorship – PIG Architects.

Lifts are vertical transport devices used to move people and loads and are an essential element of modern multistorey buildings. Lift can be equipped with electric, hydraulic, or pneumatic drives. In the described project, lift cabins with gearless drives, without machine rooms, and with landing doors compliant with fire safety requirements were installed according to the lift guidelines of the selected company. The dimensions of the lift cabs are 110 × 140 cm. There are 15 lifts in the described project. Figure 8 shows an example of the first floor of the building B3.

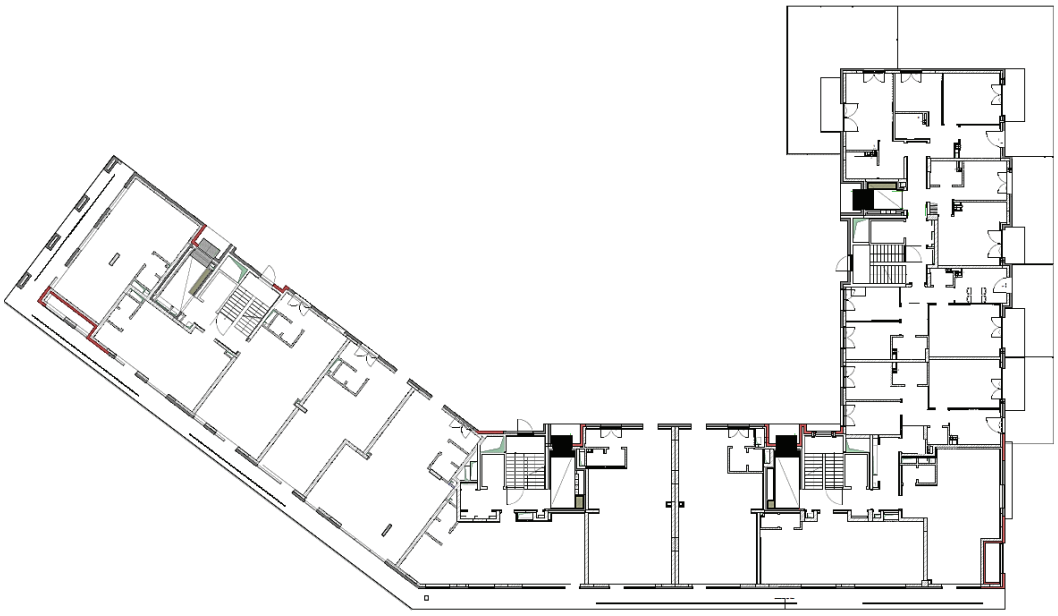


Fig. 8. First floor plan of building B3

Source: Authorship – PIG Architects.

Figure 8 shows the subdivisions for each block entrance staircase, the apartments and the service spaces. The figure also shows the wall thicknesses used to divide the individual rooms in the apartments, between the units and the separation walls between the service and residential areas.

RESULTS AND DISCUSSION

The investment described was developed between 2022 and 2024 and was affected by events such as COVID-19, inflation, and the ongoing armed conflict in Ukraine. All these factors had a significant impact on the duration of the construction. Figure 9 presents a timeline that includes external events and the timeframe of the described investment for the work covered in the analysis: window joinery, masonry walls, and the installation of the lifts and balconies.

Figure 9 presents a timeline of all the described events. It is evident that the COVID-19 pandemic was the first to occur, resulting in a lockdown. For a year, the state operated within a limited scope of its activities and capabilities. Next, an armed conflict broke out with Poland's eastern neighbours, which also significantly contributed to restrictions in the functioning of the state, including in the construction sector. Shortly after that, inflation reached its highest level, which was 13.9%. This affected all sectors of the economy, including the construction materials sector. At the same time, the described investment commenced, which lasted until January 2024, when the construction manager submitted the completion report for the works. Based on the construction data, comparative tables of time were created for the specified construction works related to bringing the construction to a state of raw closure, and then bar charts and Gantt charts were created. Figures 10–16 present a comparison of the number of days spent on a given task to the number planned during the investment schedule creation stage. Figure 10 shows the time for building masonry. It takes into consideration the time of both the plan and the actual implementation.

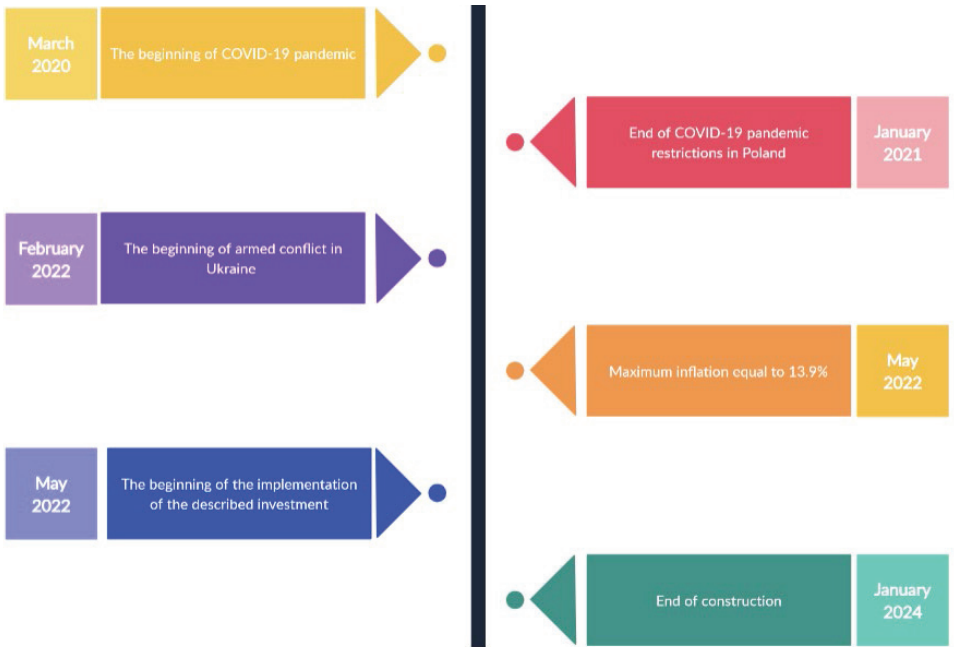


Fig. 9. Timeline that considers external events and the time of the described investment's creation

Source: own work.

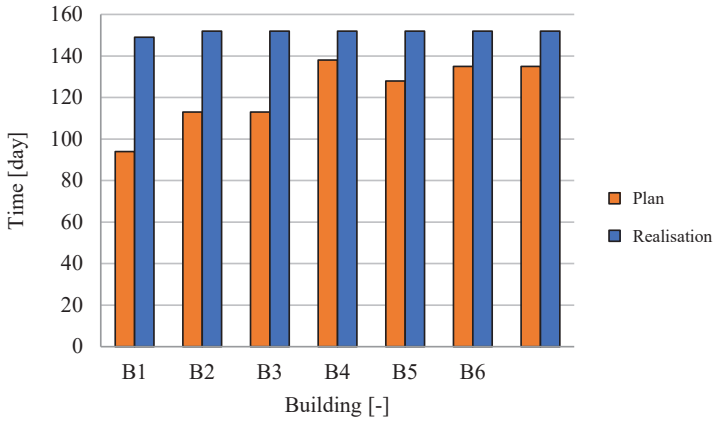


Fig. 10. Completion time for masonry walls

Source: own work.

Further to this, Figure 11 shows the timeline for building the masonry walls, but with the specific end-dates for completion. The construction of the masonry walls experienced delays, which are illustrated in Figures 10 and 11. Both figures show that the execution time significantly deviated from the schedule. The delay was sometimes up to a month. The commencement of construction on buildings B2, B3, and B5 was delayed by a period of several to a dozen days in comparison to the original schedule.

Furthermore, the projected completion date for building B2 was extended by up to two months. The work on buildings B1 and B4 started as scheduled, but the overall completion times were also delayed. However, the entire execution of the work was completed by mid-September 2023, which resulted in a total delay of approximately one month. The completion time for the masonry walls was somewhat longer than anticipated from the planned time due to the weather, staff shortages, and delayed deliveries. Figure 12 presented a summary of the time taken to complete the window installations, including delivery to site, in total days for the plan and actual completion.

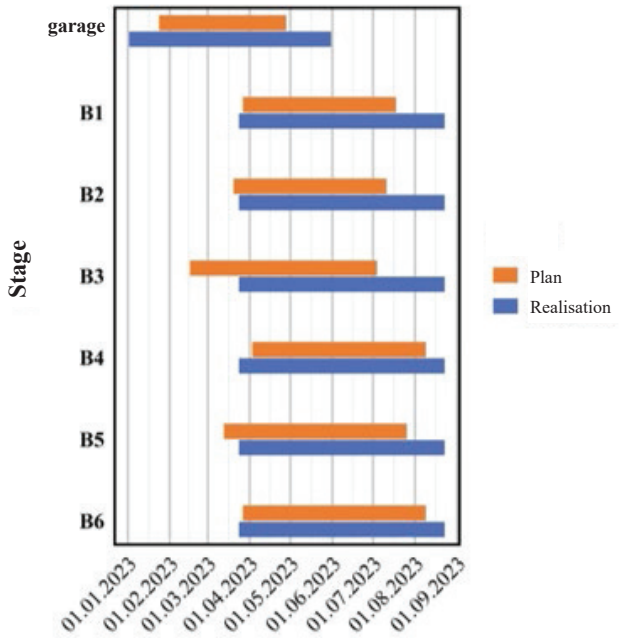


Fig. 11. Completion time for masonry walls

Source: own work.

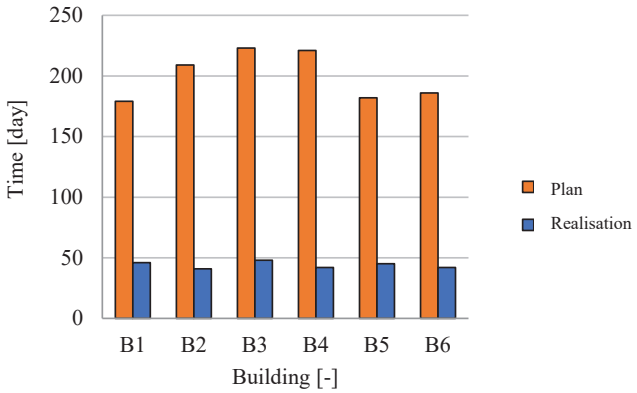


Fig. 12. Summary of time for the installation of window frames

Source: own work.

For a better comparison, Figure 13 also shows the time taken to complete the window installation according to plan and the actual completion time, but with specific dates taken from the construction logbook. Figures 12 and 13 present the time taken for the installation of the window joinery for the described investment. The basic unit in the scheduling process is working days. The indicated time discrepancies in the figure bring attention to the quick execution time of this work. For all buildings, the completion period did not exceed 50 working days.

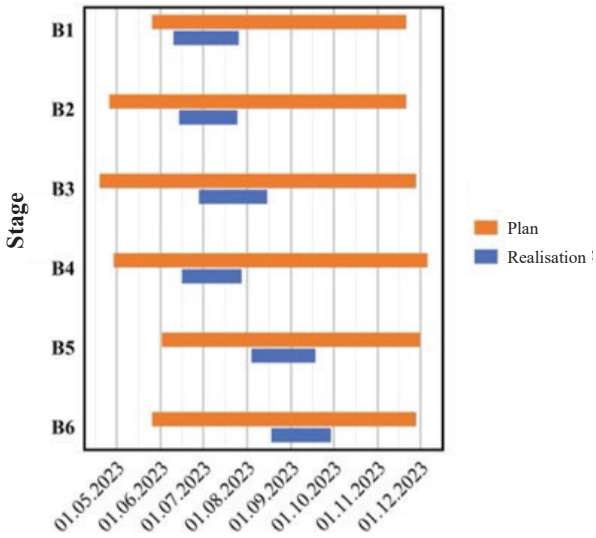


Fig. 13. Summary of time for the installation of window frames

Source: own work.

The deadlines set during the design phase were significantly longer; for buildings B3 and B4, they were around 220 working days. An additional figure based on the data regarding the time taken for the window joinery is presented using a Gantt chart. It also shows the time frame for completing a given task, but it considers specific dates. In the diagram, one can observe the time, but for specific months during which the window installation took place. All buildings were equipped with windows between June and October. The installation of the window joinery was planned for so many days because the plan scheduled the masonry walls in each of the buildings to be completed in different time frames, along with the time spent on defect repairs.

Figure 14 illustrates the time schedule for the installation of the prefabricated balconies and the lifts in the individual staircases, showing both the periods planned based on the time schedule and the actual installation times.

Figure 15, similar to Figure 14, presents a summary of the time required to complete the installation of the balconies and lifts, but with the specific start and end dates for each task. The installation of the partitions and railings took place during the finishing stage, after the painting of the facade. The implementation of the aforementioned work on the balconies began with a significant delay of almost a month and a half.

The work began at the end of October 2023 and was completed, also with a delay, at the end of December of the same year. However, the delay did not significantly affect the execution of other construction work on the described facility. The delay in the installation of the balconies resulted from the small crew size and mistakes in the execution of an order. The second element presented in Figures 14 and 15 is the lifts,

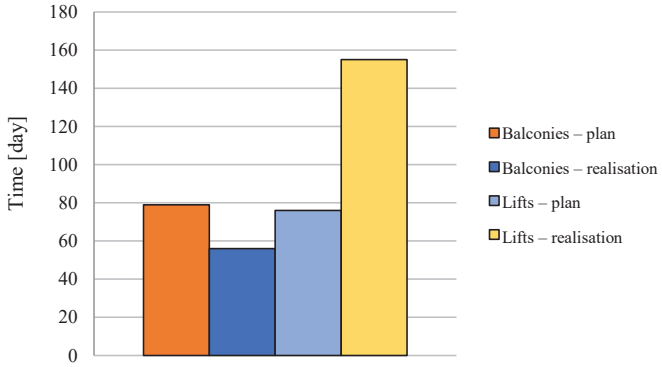


Fig. 14. Installation of balcony railings and partitions, delivery and installation of lifts

Source: own work.

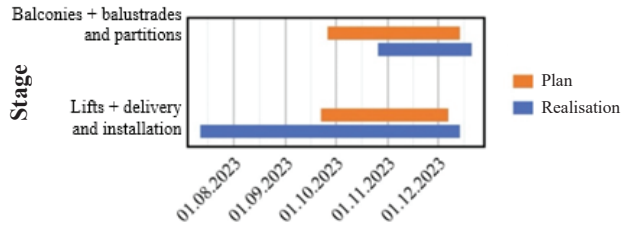


Fig. 15. Installation of balcony railings and partitions, delivery and installation of lifts

Source: own work.

specifically their delivery and installation. A significant change in the timeline for project completion has been noted on the Gantt chart showing information about the specific dates. The schedule planned for completion in the months of October to December. However, the entire process began much earlier, as early as at the end of July 2023. The lift turbines were delivered successively, and their installation took place within a few days of delivery. Despite starting this process without delay, the completion deadline was extended somewhat compared to the plan. This delay was a result of bad weather, as these days saw heavy rain that flooded the lift shafts, and their installation had to wait until the water dried out. The extension was about 15–20 working days. Nevertheless, the delay was not significant, and its postponement to the end of December 2023 did not affect the other deadlines. However, the plan was shorter than the implementation because the order was delivered faster than expected, which is shown in Figure 16. A summary of all the tasks described in the article is shown in Figure 16, which provides the time taken to complete each task, as well as the specific start and end dates. For each of the tasks listed, the planned and actual execution times are shown.

The specified works began approximately eight months after the start of the investment, that is, from May 2022. Additionally, the submission of the acceptance protocol for the investment and the handover of the property to the client were completed within five months. Table 4 shows a comparative summary for the described works, planned execution time, completion time and percentage of delays.

Table 4 presents a time comparison for the schedule and execution of the investments for the described works. The dates listed in the table show the times for individual and selected stages of project implementation.

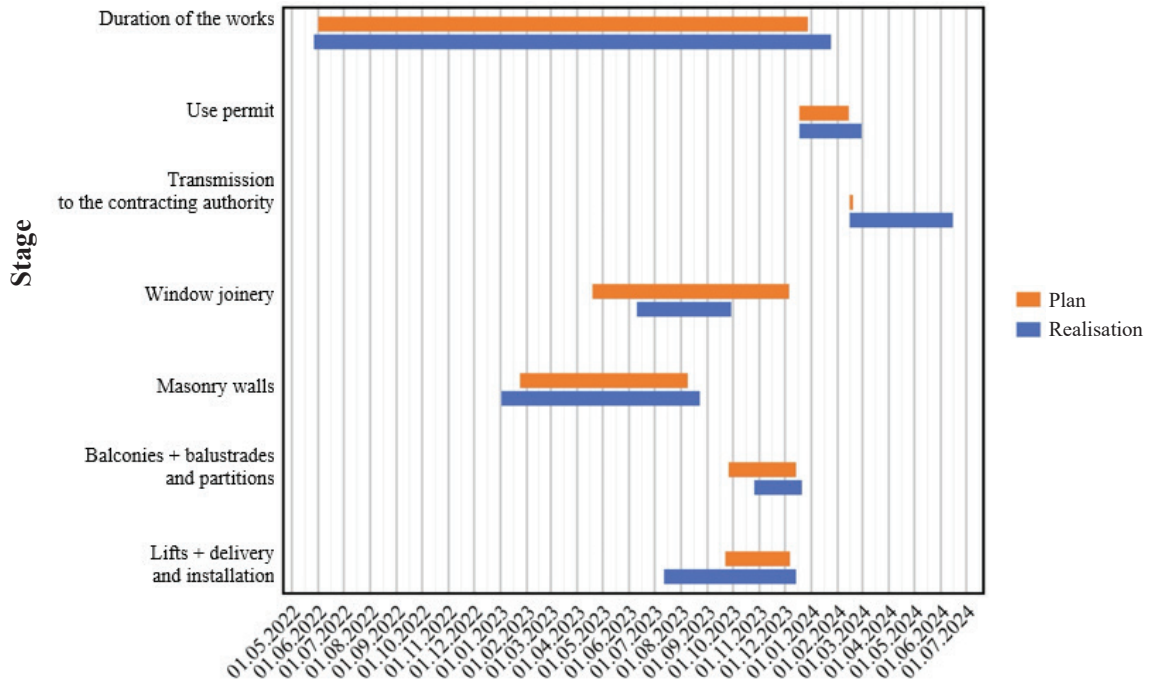


Fig. 16. Comparison of schedule time and implementation for the listed works

Source: own work.

Table 4. Summary: comparison of schedule time and implementation for the listed works

Type of work	Building	Scheduled time [days]	Implementation time [days]	Difference [days]	Time extension/ /reduction [%]
Window joinery	B1	179	46	133	74
	B2	209	41	168	80
	B3	223	48	175	78
	B4	221	42	179	81
	B5	182	45	137	75
	B6	186	42	144	77
Masonry walls	garage	94	149	−55	−59
	B1	113	152	−39	−35
	B2	113	152	−39	−35
	B3	138	152	−14	−10
	B4	128	152	−24	−19
	B5	135	152	−17	−13
	B6	135	152	−17	−13

Table 4 (cont.)

Type of work	Building	Scheduled time [days]	Implementation time [days]	Difference [days]	Time extension/ /reduction [%]
Balconies – railings and partitions	B1–6	79	56	23	29
Balconies – assembly	B1–6	–	98	–	–
Lifts – delivery and assembly	B1-6	76	155	−79	−104
Beginning of the work	–	18.05.2022	01.06.2022	14	–
Protocol for the completion of work	–	24.01.2024	28.12.2023	27	–
Occupancy permit	–	14.02.2024	29.02.2024	15	–
Transfer to the ordering party	–	19.02.2014	15.06.2024	3,769	–

Source: own work.

The presented table shows the percentage discrepancy between the duration of completing a given task in days. It can be observed that the difference in the investment completion time is about four months. What does it mean that the transfer of the construction object to the client was delayed? The remaining stages did not undergo significant changes. For the window joinery, the execution time was shortened, compared to the execution of the brick walls, which was extended by almost 60% for the garage. This was one of the stages of implementation that, due to its delay, required delaying subsequent stages of the work, such as the installation of the window joinery, which was planned for 180 to 220 days because the plan defined that the masonry walls in each of the buildings would be completed at different times, along with the time spent on defect repairs. What is more, the delivery of the windows was stretched over time. Table 4 shows the plan's time and lead time in days. However, the masonry walls were built faster than the plan anticipated, so the window joinery was completed in less time. In addition, the construction crew for the windows was sizeable, which made it possible for the task to be completed more quickly.

In the case of the balconies, the technology used for their construction was changed; prefabricated balconies were used, which accelerated their execution time. This is a creative approach by the engineers that significantly reduced the time for the execution and installation of the balconies by utilising available solutions in the construction market. The balcony partitions and railings were installed in 30% less time than allocated during the design phase. For the lifts, the set time differed by only four days compared to the execution time. The total duration of the investment according to the schedule was 642 days, which is just under 92 weeks, while the actual implementation took 745 days, resulting in 107 weeks of work. The described development of six blocks with underground parking and landscaping was built during COVID-19 and the war on the Ukrainian territory. This fact meant that the construction had to face staff shortages, delayed deliveries, and inflationary increases in the construction sector. Despite this, the investment was built only three months behind schedule.

CONCLUSIONS

Given the considerable scale of the investment, it is evident that a detailed work schedule is essential at the design stage to ensure the successful and efficient implementation of the project, which presents a significant challenge. A schedule makes it easier to plan orders, manage construction teams, and hire additional labour. One of the factors motivating construction contractors is financial penalties, which

in the case of such large investments can reach up to 20% of their costs. Of course, there are also reasons that can delay certain stages of the work, which may significantly impact subsequent tasks. In the case of the described investment, the total implementation time was extended by 103 days, resulting in a delay of over three months. The halt in work was mainly due to a lack of manpower and delays in material deliveries. However, inclement weather was also a contributing factor to the delays. A creative solution was the use of prefabricated balconies, which were installed during the construction of each floor. Such an approach demonstrates flexibility and a tailored search for new solutions, as well as adaptability to changes and the current challenges faced daily on the construction site. As a result, we can engage in effective discussions about proper investment management and create new action plans for future constructions. Despite the delays in some phases, the construction did not come to a standstill and continued to progress with the next stages of work, independent of the existing delays. The project was completed, and the premises handed over to the client, and then to their owners. This outcome underscores the importance of adaptability and innovative problem-solving in construction management, contributing valuable insights for future large-scale investments. The article presents a comprehensive and systematic analysis of case studies within the construction sector with the aim of highlighting the potential benefits of the investment under consideration. By systematically analysing the case studies, the paper demonstrates that construction companies can gain valuable insights from this investment, particularly with regard to the importance of flexibility in construction practices, as evidenced by the incorporation of prefabricated balconies. In addition, the article evaluates alternative investment delivery methods that could be effectively implemented in other construction projects to optimise outcomes. Although the investment described is a single case, it may highlight common issues that arise on comparable sites in large urban conurbations. This provides a basis for future research and practical applications in construction management.

Authors' contributions

Conceptualisation: K.W. and J.D.; methodology: K.W. and J.D.; formal analysis: K.W. and J.D.; investigation: K.W.; resources: K.W.; data curation: K.W.; writing – original draft preparation: K.W.; writing – review and editing: K.W. and J.D.; visualisation: K.W. and J.D.; supervision: J.D.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Adamczak-Bugno, A. (2023). Waloryzacja, optymalizacja i dywersyfikacja sposobami na poprawę sytuacji w budownictwie. *Nowoczesne Budownictwo Inżynieryjne*, *6*, 23–32.

Czajkowska, A. (2021). Ocena zmian na rynku kredytowym dla gospodarstw domowych w okresie pandemii. In M. Kaleta, M. Laska, D. Żuchowska (Eds), *Współczesne uwarunkowania i dylematy polityki gospodarczej* (pp. 54–66). Toruń: Wyższa Szkoła Kultury Społecznej i Medialnej w Toruniu.

Czapla, A. (2020). Istota funkcjonowania hurtowni budowlanych jako wsparcia logistycznego usług w budownictwie [The essence of the operation of construction wholesalers as logistic support for construction services]. *Gospodarka Materiałowa i Logistyka*, *10*, 29–37. https://doi.org/10.33226/1231-2037.2020.10.4

Czech, K., Karpio, A., Wielechowski, M. & Woźniakowski, T. (2020). *Polska gospodarka w początkowym okresie pandemii COVID-19*. Warszawa: Wydawnictwo SGGW.

Dutka, P., Stołecka, A. & Janiak, M. (2021). Transparentność w relacjach z kontrahentami na przykładzie spółki Budimex i przedsiębiorstw działających w tej samej branży w latach 2018–2020 oraz w trakcie pandemii COVID-19 [Transparency in Relations with Contractors: the Case of Budimex and Other Construction Companies Operating in 2018-2020 and during the COVID-19 Pandemic]. *Debiuty Naukowe Studentów Wyższej Szkoły Bankowej*, *21* (21), 47–64.

Halfen (2020). Łączniki balkonowe Halfen hit. *Katalog techniczny*. Retrieved from: https://www.halfen.com/PDF-Dateien/Druckschriften/Technische%20Produktinformationen/PL/HIT_Leviat_18-1-PL.pdf [accessed: 14.01.2024].

Kałuża-Kopias, D. (2023). Potencjał rozwoju srebrnej gospodarki w Polsce w nadchodzących latach. In W. Koczur (Ed.), *Ekonomiczne konsekwencje przemian demograficznych* (pp. 148–163). Warszawa: Rządowa Rada Ludnościowa, Główny Urząd Statystyczny.

Kaźmierczak, D. (2021). Znaczenie sektora budownictwa dla krajowej gospodarki w latach 2016–2020. *Nowoczesne Budownictwo Inżynieryjne*, *1*, 28–31.

Kłosowska, A. (2022). Sytuacja finansowa przedsiębiorstw z sektora budownictwo w Polsce w czasie pandemii COVID-19 [Impact of the COVID-19 pandemic on the financial situation of enterprises from the construction sector in Poland]. *Nierówności Społeczne a Wzrost Gospodarczy – Social Inequalities and Economic Growth*, *71* (3), 132–141.

Kraska, E. M. & Kot, J. (2024). Wpływ pandemii koronawirusa na sytuację finansową branży budowlanej [Financial Effects of the Coronavirus Pandemic on the Construction Industry]. *Przegląd Prawno-Ekonomiczny – Legal and Economic Review*, *2*, 75–98. https://doi.org/10.31743/ppe.16606

Łaszek, J., Olszewski, K. & Augustyniak, H. (2024). How the War between Russia and Ukraine Caused a Multi-Cycle in the Polish Housing Market. *Critical Housing Analysis*, *11* (1), 15–30. https://doi.org/10.13060/23362839.2024.11.1.561

Liu, L. (2020). Emerging study on the transmission of the Novel Coronavirus (COVID-19) from urban perspective: Evidence from China. *Cities*, *103*, 102759. https://doi.org/10.1016/j.cities.2020.102759

Marcinkowska, M. (2022). „Wakacje kredytowe" – analiza potencjalnych skutków regulacji dla kluczowych interesariuszy [„Credit holidays" – an analysis of the potential effects of the regulation on key stake-holders]. *Finanse i Prawo Finansowe – Finance and Financial Law*, *2* (34), 125–159. https://doi.org/10.18778/2391-6478.2.34.03

Marecik, M. (2024). Ocena wpływu pandemii COVID-19 na funkcjonowanie systemów zarządzania jakością, bezpieczeństwem i środowiskiem na przykładzie wybranych przedsiębiorstw [A Study of the Impact of Pandemic COVID-19 on the Functioning of Quality, Safety and Environment on the Example of Selected Enterprises]. *Management and Quality – Zarządzanie i Jakość*, *6* (1), 91–105.

Markowska, M. & Strahl, D. (2022). Zatrudnienie w województwach Polski w 2020 roku – pierwszy rok pandemii [Employment in Poland's provinces in 2020, the first year of the pandemic]. *Zeszyty Naukowe Uniwersytetu Ekonomicznego w Krakowie – Cracow Review of Economics and Management*, *4* (998), 29–52. https://doi.org/10.15678/znuek.2022.0998.0402

Nurzyński, J. (2002). Przeszklone przegrody budowlane i ich izolacyjność akustyczna [Building partitions with glazing and their sound insulation]. *Prace Instytutu Techniki Budowlanej – Kwartalnik – Building Research Institute – Quarterly*, *1* (121), 49–54.

Polski Komitet Normalizacyjny [PKN], (2016). *Okna i drzwi – Norma wyrobu, właściwości eksploatacyjne. Część 1: Okna i drzwi zewnętrzne bez właściwości dotyczących odporności ogniowej i/lub dymoszczelności* (PN-EN 14351-1:2006+A2:2016).

Polski Związek Pracodawców Budownictwa [PZPB], (2023). *Pismo z 30 maja 2023 roku do ministra Andrzeja Adamczyka w sprawie pilnego podjęcia działań zaradczych wobec skutków utrzymujących się nadal na polskim rynku budowlanym wysokich cen materiałów i robocizny oraz kosztów finansowania* (PZPB/34/2023OIGD/69/2023). Warszawa. https://pzpb.com.pl/wp-content/uploads/2023/07/Pismo-PZPB_OIGD_do-MI_ws-waloryzacji.pdf [accessed: 14.01.2024].

Siewiera, A. (2018). Analiza ryzyka w procesie zarządzania projektem budowlanym [Risk analysis in the construction project management process]. *Zeszyty Naukowe Uniwersytetu Szczecińskiego Finanse Rynki Finansowe Ubezpieczenia*, *92*, 175–184. https://doi.org/10.18276/frfu.2018.92-15

Sitek, M. (2022). Czas jako wartość w budownictwie. *Nowoczesne Budownictwo Inżynieryjne*, *4*, 24–35.

Sosna, B. (2022). Wojna w Ukrainie zagrożeniem dla rentowności polskiego budownictwa. *Nowoczesne Budownictwo Inżynieryjne*, *3*, 92–93.

Szruba, M. (2021). Czas na budownictwo – budownictwo na czas. *Nowoczesne Budownictwo Inżynieryjne*, *4*, 18–27.

Ustawa z dnia 7 lipca 1994 r. – Prawo budowlane (Dz.U. 1994 nr 89 poz. 414).

Węgrzyn, P. & Topczewska, A. (2023). Związek między wojną w Ukrainie a kształtowaniem się relacji depozytów do kredytów w bankach w Polsce [The relation between the war in Ukraine and the deposit-to-loan ratio of banks in Poland]. *Bank i Kredyt – Bank and Credit*, *54* (2), 129–152. https://doi.org/10.5604/01.3001.0054.5703

Yang, Z. & Junjie, X. (2023). Research and Application of Intelligent Construction in Prefabricated Building Construction. *Sustainability in Environment*, *8* (3), 42–49. https://doi.org/10.22158/se.v8n3p42

Związek Przedsiębiorców i Pracodawców [ZPP], (2021). *Podsumowanie lockdown-u w Polsce*. Warszawa. Retrieved from: https://zpp.net.pl/wp-content/uploads/2021/01/25.01.2021-Business-Paper-Podsumowanie-lockdownu-w-Polsce.pdf [accessed: 14.01.2024].

ANALIZA WPŁYWU GLOBALNEGO KRYZYSU W LATACH 2021–2024 NA CZAS REALIZACJI INWESTYCJI BUDOWNEJ BLOKÓW WIELORODZINNYCH

STRESZCZENIE

Praca opisuje harmonogram realizacji projektu budowlanego obejmującego sześć budynków mieszkalnych, tereny zielone oraz plac zabaw. Projekt realizowano w Warszawie w latach 2022–2024. Inwestycja została podjęta po znaczących wydarzeniach, takich jak: pandemia COVID-19, wzrost inflacji oraz konflikt zbrojny na Ukrainie. Studium skupia się na analizie wybranych etapów prac budowlanych przeprowadzonych w ramach inwestycji. Szczególną uwagę zwrócono na takie zadania, jak: montaż stolarki okiennej, budowa wewnętrznych ścian murowanych, instalacja ścianek działowych i balustrad balkonowych, a także dostawa i montaż wind. Ponadto zbadano ogólne dane dotyczące postępu prac, harmonogram budowy oraz wpisy z dziennika budowy odnoszące się do konkretnych terminów zakończenia poszczególnych etapów. Na podstawie dostarczonych danych przeprowadzono analizę porównawczą czasu potrzebnego na ukończenie poszczególnych zadań budowlanych względem harmonogramu ustalonego w fazie planowania projektu. W artykule poruszono kwestie związane z dotrzymaniem terminów w dużych przedsięwzięciach budowlanych, w przypadku których zastosowana technologia, liczba personelu oraz skala inwestycji przyczyniają się do wydłużenia procesu budowlanego przez wykonawcę.

Słowa kluczowe: harmonogram, czas realizacji projektu, proces inwestycyjny, globalny kryzys, budownictwo mieszkaniowe wielorodzinne

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INTEGRATION OF ARCHITECTURE AND ART IN THE WORKS OF LUDWIG PETER KOWALSKI

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ABSTRACT

The article addresses the issue of integrating architecture and stained glass art using the example of Ludwig Peter Kowalski, an outstanding artist, one of the most outstanding stained glass designers of the 20th century, and a renowned academic lecturer at art schools in Wrocław and Berlin. The aim of the project was to formulate functional, formal, technical, and design recommendations. The research was conducted both in Poland and, above all, in Berlin. A mixed-methods approach was used here, combining multiple case studies and qualitative research, including archival research and in situ analysis.

Keywords: Ludwig Peter Kowalski, Deutsche Künstlerbund, stained glass, art, architecture

INTRODUCTION

Ludwig Peter Kowalski was a painter, promoter of applied art, and a renowned academic lecturer at art schools in Wrocław and Berlin. This versatile Silesian artist is considered one of the most outstanding stained glass designers of the 20th century. Only the small part of his works preserved in Silesia in architectural structures created before 1945 highlights his great talent. This article attempts to analyse the selected, most famous works of the artist, designed in connection with architecture. The research was conducted both in Poland and primarily in Berlin, with which he linked his private and professional life after 1945. The research project was carried out thanks to a university grant from the State Academy of Applied Sciences in Nysa.

STATE OF RESEARCH, RESEARCH OBJECTIVE, RESEARCH METHOD

Literature on the work of Ludwig Peter Kowalski is not abundant. The first analyses of the artist's work were published in Silesian cultural magazines as early as the 1920s (Muschler, 1926). His professional activity was also mentioned in a monograph devoted to pre-war Chorzów (Schmidt, 1941). In addition, Kowalski and his artistic activity were and are constantly present in studies devoted to the Wrocław artistic environment (Hartung, 1967; Kern, 2018). After 1945, the artist's achievements were the subject of analyses in German and Polish publications. Unfortunately, awareness of his work in Poland is negligible.

The aim of the project was to examine the work of Ludwig Peter Kowalski in connection with stained glass art and architecture in particular, and to attempt to formulate functional, formal, technical and design

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recommendations. In order to obtain a coherent and comprehensive answer to the research problem, mixed--method research was conducted, combining a multi-case study and qualitative research. After collecting data, conducting in situ research and analysing empirical evidence, an attempt was made to systematise the knowledge obtained and confront it with new datasets. An attempt was also made to formulate further research questions.

In the first stage, a review of the literature available in digital library resources was conducted, including the Opole Digital Library, the Lower Silesian Digital Library and the Silesian Digital Library. Then, queries were conducted in the Museum of Architecture in Wrocław, the State Library in Berlin and the Deutschlandhaus Foundation in Berlin. During the entire study, confrontations were made with new datasets, including those based on a review of literature on the broadly understood issue of stained glass. Thanks to the kindness, knowledge and commitment of the owners and managers of the buildings in Berlin, it was possible to conduct in situ research and obtain additional information on the work of Ludwig Peter Kowalski. The substantive support of Erik Venhorst, a specialist in Construction and Art at the Archbishop's Ordinariate in Berlin, proved particularly important here. The research was conducted on selected public buildings in Berlin and in Poland on the only preserved monumental work of stained glass art in Nysa.

The selection criteria were:
– availability of individual preserved objects,
– diversity of architectural objects in which the artist designed and executed works, including in the context of their function, form and location,
– influence of stained glass, mosaics or frescoes on the perception of architecture.

Among the works located in Poland, the artist's work and connection with architecture is best represented by the preserved set of stained glass windows in Nysa. Abroad, the largest number of works in architectural objects of various functions, dates of creation and size can be found in Berlin. The research was conducted in situ, analysing the preserved state of the works, especially stained glass windows, and the universality of the subject matter related to a specific interior of the building or to the entire building, taking into account the challenge of creating a contemporary, expressionist work in a historical object. During the research, detailed documentation of the stained glass windows was made. Thanks to consultations with the users of the objects and a review of the literature, it was possible to read the symbolic layer of works with religious or secular themes.

SHORT BIOGRAPHY OF THE ARTIST

Ludwig Peter Kowalski was born on 1 August 1891 in Nowe Hajduki, a district of Chorzów, and died on 5 July 1967 in Berlin (Wycisk-Müller, 2016). The artist studied at the State Academy of Art and Crafts in Wrocław, which, after Hans Poelzig's reforms, obtained the status of a royal academy. The lecturers of this one of the most progressive German academies were many famous architects and avant-garde artists, including Hans Scharoun, Johannes Molzahn, Oskar Moll and Oskar Schlemmer (Łukaszewicz, 1983). After the First World War, Kowalski initially worked in his own studio in Wrocław as an independent artist. In 1922, he became a member of the Silesian Association of Visual Artists, where he temporarily served as chairman. In 1928, the association was transformed into the Association of German Artists. In 1926, he joined the 1922 Group operating within the Silesian Association of Visual Artists (Stephan, 1932). He often presented his paintings at exhibitions, and his illustrations were regularly published in Silesian magazines. Many of his works had already been added to both museum and private collections.

In 1927, he was appointed lecturer at the Municipal School of Handicraft and Artistic Industry in Wrocław, at that time one of the most avant-garde art schools in Europe. He first taught a figurative drawing class, and in 1928 took over the management of the painting department. In 1934, the university's activities were deemed undesirable

by the National Socialists for political reasons, which resulted in the dismissal of professors, including Kowalski. Due to his membership in the 1922 Group, all of his works, considered 'degenerate', were consistently rejected at exhibitions. However, the artist was not deprived of the right to practise his profession. Additionally, in 1937, his work was included in the Munich Nazi propaganda exhibition called *Degenerate Art*. At the same time, in the same year, he took part in the exhibition called *Reconstruction and Rejuvenation*, organised by the National Socialists, and was also accepted to the Prussian Academy of Fine Arts in Berlin. In 1942, he received the Upper Silesian Art Award. Thus, Kowalski's artistic biography is characterised by many contradictions.

ARTISTIC CREATIVITY

Ludwig Peter Kowalski is considered one of the great stained glass designers of the last century. In addition to stained glass, he left behind numerous drawings, paintings, mosaics and frescoes and, above all, stained glass. The themes of his paintings included portraits, studies of human figures, still life, landscapes and urban impressions. He designed stained glass in public buildings in the years 1925–1935 and 1950–1960. He carried out the projects in close cooperation with the Berlin stained glass company August Wagner, Berlin-Treptow. Among secular objects, one can point out cultural objects, including theatres, educational objects, headquarters of public institutions and associations, railway stations, and office buildings. A significant part of the works carried out in sacral objects, including Catholic and Evangelical churches and chapels, were figurative biblical representations. Kowalski designed stained glass windows, frescoes and mosaics for existing objects as well as newly designed ones. The first group includes sacral objects built at the turn of the 19th century. The second group includes designs intended for objects erected simultaneously with the creation of the artist's works. These are modernist objects. Here, cooperation between the architect and the artist was necessary and possible. In the objects created earlier, the artist had to adapt in terms of the form, size and content of the work. Both stained glass, frescoes and mosaics designed and implemented in various techniques, formal and compositional solutions defined the spaces of the objects in a specific way. All this had an impact on the dialogue with architecture, which was different in each of the objects.

Before 1945, Kowalski made a number of mosaics, frescoes and stained glass windows in public buildings, including in Gliwice, Katowice, Opole, Nysa, Kluczbork, Oława, Strzelce Opolskie and Nowa Sól. In the first period of his work, two monumental stained glass windows in Gliwice and Nysa draw attention. In Gliwice in 1940, in the new building of the Upper Silesian Association of Miners and Metallurgists in Gliwice, he designed five monumental stained glass windows decorating the hall (Kluge-Gleiwitz, 1928). Unfortunately, the stained glass windows were lost during the war. In Nysa, in 1937, in the building of the then office building of the electricity distribution company Überlandwerk Oberschlesien AG, currently the headquarters of the power plant in Nysa, the artist designed a total of ten stained glass windows (Fig. 1). This is the largest preserved collection of stained glass windows with secular themes in Silesia (Sąsiadek, 2012). The coloured glazing was designed on two storeys of the building, directly above the ground, almost the entire height of the individual storeys, and constitutes the only strong lighting of the open spaces next to the staircase (Opałka, 2013). The stained glass windows located on the first floor depict historical figures who built the myth of German statehood. The works on the second floor are an apotheosis of work and craft. These are genre scenes of bakers, farmers, butchers and fishermen. This is a common theme in Kowalski's work (Müller-Hofstede, 1940).

The artist also painted frescoes in the Katowice municipal theatre, secondary schools, including those in Opole and Nowa Sól, and in the hall of the Polish State Railway station in Strzelce Opolskie in the years 1934–1936. A monumental mosaic with the Resurrected Christ was created in the cemetery chapel in Półwieś, a district of Opole. In Oława, the altar made in 1934–1935 has been preserved in the parish church. The stained glass windows of the choir in the Church of St. Camillus in Charlottenburg, a district of Berlin, built in 1930–1932, were destroyed in 1943 and have not survived to this day.



Fig. 1. Office building of the power plant in Nysa (1937). The apotheosis of work and craft: a – blacksmithing, b – fruit growing

Source: photo by the author.

Ludwig Peter Kowalski, like the entire German population, was forced to leave his home in 1945. He then irretrievably lost his studio and almost all of his artistic achievements. After the war, he linked his professional and private life with Berlin. He first worked in East Berlin as a professor of art at the Academy of Fine Arts in Weissensee, before moving to West Berlin in 1948. At that time, he created stained glass windows in a variety of styles for secular and religious buildings of various denominations. These included the stained glass windows in the churches of St. Rita, St. Elizabeth, St. Ansgar, Sacred Heart of Jesus, Emperor Frederick Memorial Church, and Luisenkirche. He also created stained glass windows in the conference room of the Bundeshaus in Berlin, in the foyer of the Schiller Theatre, as well as stained glass windows in the chapel of the Catholic student residence Wilhelm-Weskamm-Haus in Charlottenburg, a district of Berlin, and in the meeting room of the district council of the city hall in Kreuzberg, a district of Berlin. Outside Berlin, he created stained glass windows for the baptistery of the parish church in Neuwied, the Berufsgenossenschaft trade association headquarters in Mannheim, the Navy Memorial Church in Wilhelmshaven, the House of the German East in Munich, the cemetery chapel in Wolfsburg, and mosaics for the Church of St. Philip Neri in Lima, Peru.

In 1950, Kowalski made stained glass windows for the exhibition called *German Homeland in the East* in Berlin. In 1975, the works were installed on the staircase of the Deutschlandhaus building in Kreuzberg, a district of Berlin. Currently, the stained glass windows are displayed in the same building on one of the pillars in a way that prevents their full viewing (Fig. 2). The works depict three lost areas of former Germany – East Prussia, Silesia and Pomerania – which symbolise agriculture and horse breeding, mining and flax weaving, and agriculture and fishing, respectively.

In 1952, in the Bundeshaus Wilmersdorf building, the seat of the representative of the federal government before the unification of Germany, Kowalski made stained glass windows with 24 German coats of arms. This type of work was often done by the artist. He placed the coats of arms of cities in stained glass windows in Gliwice and Nysa, among others.

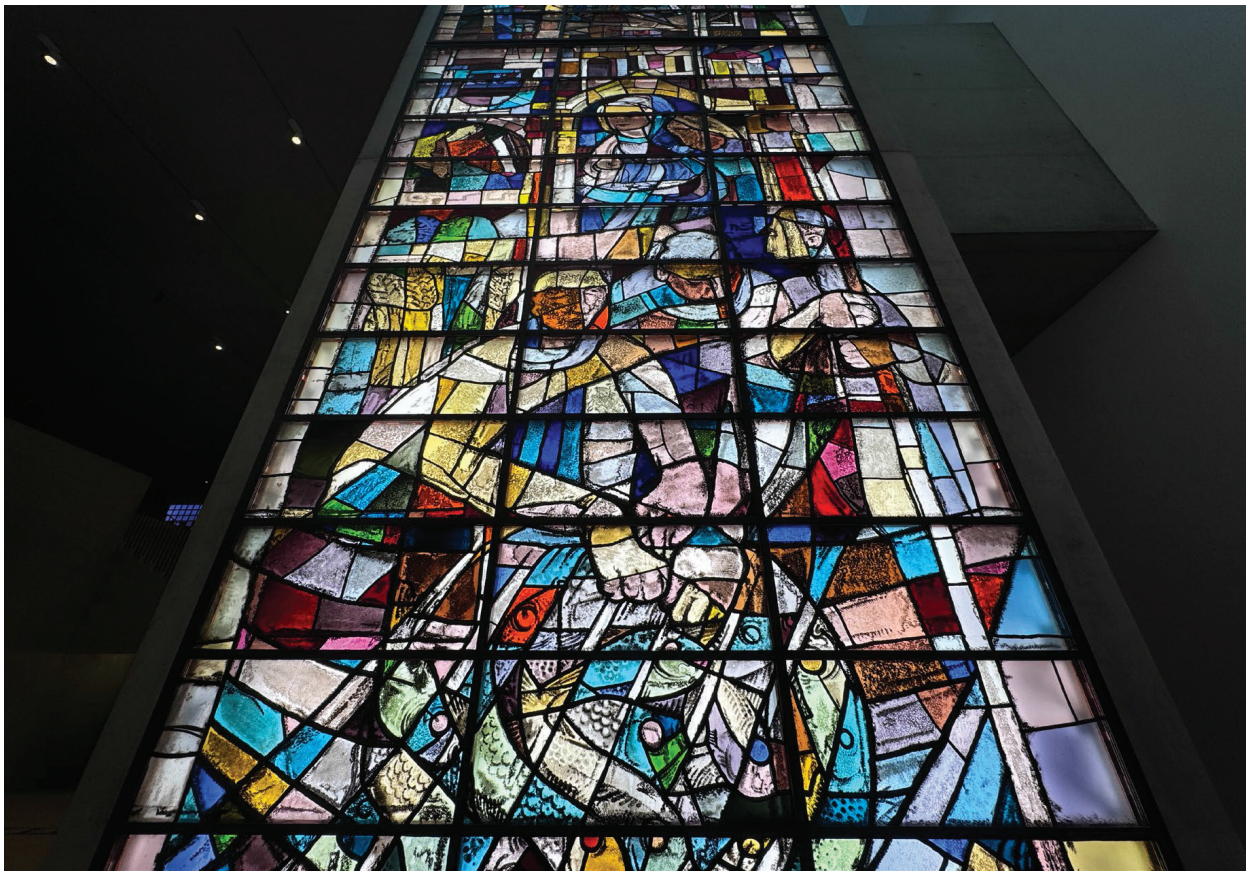


Fig. 2. Fragment of a stained glass window made for the German exhibition *Homeland in the East* (1950) in Kreuzberg. Fishing symbolising Pomerania

Source: photo by the author.

Also, in 1950, in the Schiller Theatre in Berlin, which was being rebuilt after World War II, the artist created an impressive monumental façade of polished glass (Fig. 3). The glass wall in the main foyer of the theatre is 25 m long and 5.20 m high. In the evening and at night, appropriately illuminated, it becomes a dominant feature in the body of the building. The artist presented abstract and surreal figures here and ornaments with motifs of both tragedy and comedy. Thanks to the colouristic integration, the whole is very coherent and not distracting. This is a very important project. The stained glass is not viewed only from the interior of the building – here, the foyer, but above all, most often from the outside. The elevation remains white during the day. However, in the evenings, it can be illuminated in colours consistent with the presented repertoire. The glass wall then becomes a dominant feature. From the inside, white, intricately cut glass limits the view to the outside. Thanks to this, the viewer, even during the day when the elevation is not illuminated, is not distracted by the everyday life, including traffic on the street. They are in a temple of art.

During the reconstruction of the Protestant Luisenkirche church in the Berlin district of Charlottenburg in the years 1950–1956, destroyed as a result of an Allied air raid in September 1943, the artist designed four stained glass windows in the eastern wing of the temple, filled with the magic of spiritual figures. The stained glass windows, dated 1954, 1955 and 1956, present scenes from the Old Testament (Fig. 4). The biblical figures

exude seriousness and dignity, evoking associations with medieval paintings. In a similar poetics, the artist made a round stained glass window in the Catholic church of St. Rita, located in the peripheral Berlin district of Reinickendorf. The stained glass window placed in the presbytery, centrally on the wall behind the altar, is a dominant feature in the modestly equipped temple. In other words, the entire interior design is subordinated to Kowalski's work. The stained glass window shows Christ Pantocrator in a mandorla in a standing position with a closed Holy Scripture in his right hand and his left hand raised in a gesture of blessing (Fig. 5).



a

b

Fig. 3. Schiller Theatre in Berlin (1950): a – general view; b – view from the foyer

Source: photos by the author.



Fig. 4. Luisenkirche in Berlin. Scenes from the Old Testament: a – *God gives Moses the stone tablets with the Ten Commandments* (1955); b – *Abraham's Sacrifice* (1954)

Source: photo by the author.



Fig. 5. *Christ Pantocrator*, St. Rita Church, Berlin

Source: photo by Erik Venhorst.

In 1957, in the Church of the Sacred Heart of Jesus (*Herz-Jesu-Kirche*), a combination of neo-Gothic and neo-classical elements, located in the Berlin district of Charlottenburg, Ludwig Piotr Kowalski created three stained glass windows in the apse of the presbytery. In the stained glass windows, the artist presented scenes related to the miracles, suffering and Resurrection of Christ and the life of the Holy Family. Also, in this case, the artist created a work that does not constitute dissonance with the historical object.

All the windows in the neo-Gothic Church of St. Elizabeth from 1911, located in the Berlin district of Schöneberg, were destroyed during World War II. In 1960–1961, Ludwig Peter Kowalski designed five large stained glass windows in this single-nave, spacious church. Against a geometric-abstract background, the artist presented dignified groups of figures frozen in lofty immobility. The hieratic nature of the figures is emphasised by Gothic robes.

During the International Architectural Exhibition Interbau, the largest German exhibition event of the 1950s, Kowalski created frescoes and stained glass windows in two newly built churches. The exhibition opened in the summer of 1957. The entire design was implemented over an area of 25 ha in the Hansaviertel district of Berlin, which had been destroyed by war operations. More than 50 outstanding architects, including Alvar Aalto, Walter Gropius and Oscar Niemeyer, designed some 1,300 apartments, a library, two churches, a kindergarten, an elementary school and a shopping centre here. In the Protestant Emperor Frederick Memorial Church in Berlin (*Kaiser-Friedrich-Gedächtniskirche*), the artist designed five round windows (Fig. 6). Opposite the glazed eastern elevation, three works were placed on the windows above the gallery: *The Annunciation*, *The Angel Shows the Women the Empty Tomb* and *The Seven Gifts of the Holy Spirit*. The window above the central portal depicts *Luther's Rose* with the inscription *Vivit* (*He Lives*). The fifth stained glass window, distinguished by its abstract forms, is located by the southwestern staircase. Kowalski's works are illuminated by a monumental light glass wall entitled *Victory of Light* by Georg Meistermann. The construction of the church, designed by the Berlin architect Ludwig Lemmer, was carried out in the years 1955–1957.

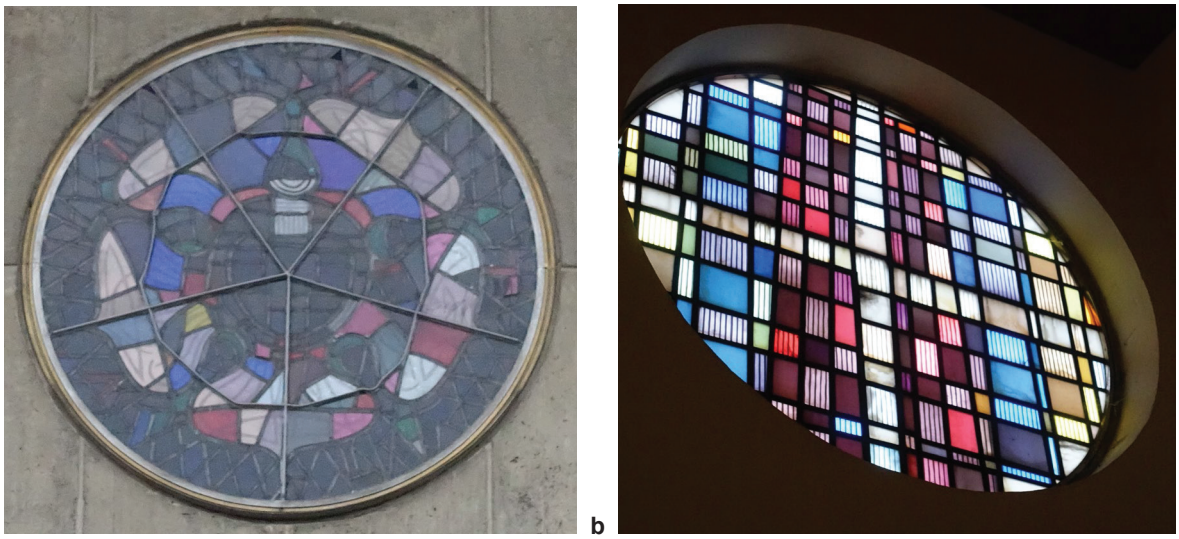


Fig. 6. Stained glass windows in the Emperor Frederick Memorial Church in Berlin (1957): a – *Luther Rose* above the central portal; b – abstract composition by the staircase

Source: photo by the author.

Also, in the same year, 1957, the Roman Catholic Church of St. Ansgar was opened. Kowalski painted a monumental fresco on the north-west wall of the temple, depicting the twenty Stations of the Cross, arranged on an arch, presenting the story of Christ's life from birth to Resurrection. This composition, deeply rooted in Christian iconography, is located opposite the almost entirely glazed south-east wall, which illuminates the interior (Fig. 7).

a



b



Fig. 7. Fresco presenting the 20 Stations of the Cross in the Church of St. Ansgar in Berlin (1957): a – general view, b – *The Entombment* (Station 14)

Source: photo by the author.

The Church of St. Ansgar was built on an open plan in the shape of a parabola, according to the design of the Berlin architect Willy Kreuer. Outside the centre of Berlin, in the Schlachtensee district, in the single-nave Roman Catholic Church of the Twelve Holy Apostles, the artist designed a mosaic cross. The cross, shimmering in shades of gold, brown and orange, designed in a semi-circular low apse, is an important element building the interior of the church. The church was built in 1953–1954. Both this mosaic and the fresco in the Church of St. Ansgar are examples of interiors in which the artist's individual works 'build' the mood of the interior.

CONCLUSIONS

In situ research, interviews with local communities, analysis of new datasets of written and iconographic material, as well as research on historical continuity over the decades from the interwar period to the first two post-war decades, expanded the knowledge on the work of Ludwig Peter Kowalski, as well as the perception of architecture, in particular in the context of stained glass art. Based on the research conducted, it is possible to articulate functional, formal, technical and design recommendations.

In the functional aspect, the work of Ludwig Peter Kowalski shows that the visual language used by the artist corresponded perfectly in objects with different functions. In particular, the phenomenon of matching contemporary, expressive language in historical objects is important here. In addition, the visual side of the works seems to be important, which, depending on the function and form of the interior, can be a dominant feature or, as in the case of Schiller's theatre, remain almost in the background. The effect of artist-architect dialogue may be the harmonious interplay of a work of art in an architectural space. Based on the collected research material, it can be stated that the artist's works are characterised by the selection of repeatable solutions in the technical execution of stained glass. The colours of the works, despite the evolution of his work, are also similar. It can therefore be assumed that it will be possible to recreate the artist's unpreserved works with modern AI tools. For example, the stained glass in the building of the Upper Silesian Association of Miners and Metallurgists in Gliwice, the only trace of which are preserved black-and-white photographs with a description of the colour scheme. The study could include a change in the perception of the interior currently lit by ordinary windows. Attempts to recreate the artist's works could bring closer the artist's technique and the stained glass workshop. If conservation work or supplementation of possibly damaged elements of the works is necessary, it would be possible to recreate them. During the implementation of the project, it would be necessary to conduct detailed physicochemical tests of the preserved works in Nysa and Berlin. Further detailed technical and historical studies could be the basis for formulating further research questions.

In terms of the technical aspect, Kowalski's works evolved from the stained glass windows in Gliwice and Nysa, which were characterised by a dense 'drawing' of lead frames, to the increasingly 'lighter', more dematerialised in space, Berlin works. Here, the supporting structure of the stained glass windows is significantly less visible. Nowadays, for reasons of utility, many churches are heated, which can also pose a threat to stained glass. It would therefore be necessary to monitor stained glass and the rooms in which they are installed.

Among the formal recommendations, it would be necessary to indicate the need to popularise the artist's works. It would be advisable to develop an interactive guide to architectural objects in which the artist's works are located. However, the most comprehensive way to learn about Ludwig Peter Kowalski's works would be to take a guided tour. Considering the preservation of the stained glass windows in Berlin and Nysa, it would be valuable to conduct research on their state of preservation, to determine potential threats and to indicate conservation measures in order to maintain their durability.

The scope of future research on preserved stained glass should include their conservation. This work should be based on traditional materials and technologies. The use of AI tools could contribute to the reconstruction of destroyed stained glass or individual elements based on the artistic and technical solutions used by the artist in other works. A broad area of research in the field of building physics would be the implementation of additional glazing for better thermal modernisation of buildings, while another interesting area of research could include the impact of stained glass light on the interiors of buildings. The limitation of the research remains the fact that most of Kowalski's works in Silesia were destroyed before 1945. These works, apart from the stained glass from Gliwice, are not documented.

Architecture influenced Kowalski's works in terms of the form, size and content of the stained glass. In addition, religious buildings influenced the content of the works. In Protestant churches, it was the biblical theme from the Old Testament, while in Roman Catholic churches, representations from the New Testament dominated. In secular public buildings, the theme met the expectations of the ordering party. In secondary schools, this was

a narrative referring to education, and in industrial facilities, it distinguished industrial builders and historical figures. In theatre facilities, for example in the Schiller Theatre, it was possible for him to create a composition combining surrealism and abstraction. An extreme, negative case of the influence of architecture on the exhibited stained glass is Kowalski's work in the Deutschlandhaus building. Here, its proper viewing is impossible.

Kowalski's work also had an influence on architecture. In the church of St. Ansgar, the Way of the Cross is the main element building the interior. Here, the artist had complete freedom in shaping the individual stations on the arch. In the Schiller Theatre, the use of white polished glass had to be a compromise between the artist and the architect. In other facilities, in particular, mosaics had an influence on the construction of the architectural interior.

The study has brought significantly closer and systematised the work of Ludwig Peter Kowalski. For the author, it also became an inspiration to examine other preserved works of 20th century stained glass art in preserved modernist buildings in Silesia. In particular, in connection with other projects by the same artists or workshops that also operated outside Poland.

REFERENCES

Hartung, H. (1967). Schlesien (Zeitschrift). *Jahrgang 12*.

Kern, A. (2018). Ludwig Peter Kowalski. Über eine widersprüchliche Künstlerkarriere zwischen Avantgarde, "deutschem Kunstschaffen" und Nachkriegsmoderne. In D. Schmengler, A. Kern (Eds), *Maler. Mentor. Magier. Otto Mueller und sein Netzwerk in Breslau* (pp. 168–177). Heidelberg: Kehrer.

Kluge-Gleiwitz (1928). Der Neubau des Staatlichen Gymnasiums in Gleiwitz. *Der Oberschlesier*, *10*, 539–541.

Łukaszewicz, P. (1983). Wrocławska Akademia Sztuki i środowisko artystyczne tego miasta 1900–1932. In Z. Świechowski (Ed.), *W kręgu sztuki śląskiej pierwszej połowy XX wieku*. Wrocław–Warszawa–Kraków––Gdańsk–Łódź: Zakład Narodowy im. Ossolińskich. Wydawnictwo PAN.

Müller-Hofstede, C. (1940). Monumentale Glasgemälde von Ludwig Peter Kowalski in Schlesien. *Schlesische Stimme*, *22* (1), 65–73.

Muschler, R. C. (1926). Ludwig Peter Kowalski. *Der Oberschlesier*, *8* (1), 16–20.

Opałka, P. (2013). Prądy artystyczne a technika na wybranych przykładach obiektów poprzemysłowych w Nysie. In J. Flizikowski (Ed.), *Integracja sztuki i techniki w architekturze i urbanistyce* (Vol. 1, pp. 269–274). Bydgoszcz: Wydawnictwa Uczelniane Uniwersytetu Technologiczno-Przyrodniczego w Bydgoszczy.

Sąsiadek, Z. (2012). *Nieznany modernizm*. AWR Edytor.

Schmidt, R. (1941). *Kleines Stadtbuch von Kőnigshütte Oberschlesien*. Berlin: Verlag für Sozialpolitik, Wirtschaft und Statistik Paul Schmidt.

Stephan, B. (1932). Breslauer Kunstausstellung „Gruppe 1922". *Der Oberschlesier*, *14* (5), 267–268.

Wycisk-Müller, Z. (2016). *Schöpferisches Schlesien von A bis Z* (Vol. 2, pp. 92–93). Leipzig: Engelsdorfer Verlag.

INTEGRACJA ARCHITEKTURY I SZTUKI W TWÓRCZOŚCI LUDWIGA PETERA KOWALSKIEGO

STRESZCZENIE

W artykule podjęto problematykę integracji architektury i sztuki na przykładzie twórczości Ludwiga Petera Kowalskiego, wybitnego artysty, jednego z najwybitniejszych projektantów witraży XX wieku, a także uznanego wykładowcy akademickiego wyższych uczelni artystycznych we Wrocławiu i w Berlinie. Celem projektu było sformułowanie zaleceń funkcjonalnych, formalnych oraz technicznych i projektowych. Badania przeprowadzono zarówno w Polsce, jak i Berlinie. Wykorzystano podczas nich metodę mieszaną, łączącą studium wielu przypadków i badania jakościowe, w tym badania archiwalne oraz analizę in situ.

Słowa kluczowe: Peter Ludwig Kowalski, Deutsche Künstlerbund, witraże, sztuka, architektura

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PREDICTING LONG-TERM STRENGTH OF COMPRESSED CONCRETE

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ABSTRACT

The article characterises the features of compressed concrete deformation under the action of long--term loads. The aim of the research presented in the article was to establish the analytical dependence of determining the long-term strength of compressed concrete. It hypothesises that the specific potential energy of its ultimate deformation (destruction) is invariant and independent of the concrete loading mode. Other researchers' critical analyses have confirmed the functional dependence of the level of long-term strength of compressed concrete not only from its standardised elastic-plastic characteristics but also from the concrete strain rate. The proposed methodology evaluation for determining the long-term strength of compressed concrete is reduced to a comparison of the relevant theoretical calculated results with the various researchers' published experimental data.

Keywords: concrete, energy model, specific potential energy, strain rate, level of long-term strength

INTRODUCTION

Studies of compressed concrete's long-term strength have become one of the determining factors in reinforced concrete theory since it came to be used in the practical design of reinforced concrete elements and structures. Therefore, it is not surprising that the most active research in this direction began in the 1930s–1960s. The first serious studies of compressed concrete's long-term strength were carried out by Graf and Brenner (1937). However, the most thorough among them was the research of Rüsch (1956, 1960), which mainly concerned concretes of low and medium strength classes. They, like other studies of this period (Shank, 1949; Sell, 1959), showed that even after a long period, the long-term strength of low-class concretes did not exceed $0.75f_c$, and that of medium-class concretes was lower than $0.8f_c$. It was also established that under such constant loads, even the further long-term hydration of cement stone in early-aged concrete is not able to stop the process of its eventual destruction. At the same time, it was noticed that at relatively moderate stress levels in compressed concrete ($\eta_c = \sigma_c/f_c = 0.4$–$0.6$), a slight positive effect of long-term loading on its strength is observed.

Subsequently, most of the high-profile studies (Yashin, 1969; Zaitsev, 1972; Prokopovich, 1978; Ngab, Slate & Nilson, 1981; Smadi, Slate & Nilson, 1985; Han, 1996; Iravani & MacGregor, 1998; Tasevski, Fernández & Muttoni, 2018; Empelmann & Javidmehr, 2020; Holovata, Neutov & Surianinov, 2021; Raupov & Malikov, 2023) were already directly or indirectly aimed at attempting to standardise the long-term compressive strength of concrete. However, modern design standards still lack clear and sufficiently substantiated recommendations for considering the influence of long-term loads in the calculations of reinforced concrete elements for limit states,

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referring here not only to the maximum safe levels of this long-term loading, but also to the modes of applying (creating) these loads. After all, it is apparent that a change in the rate of applying a load or the concrete strain rate will lead not only to a change in the safe level of long-term load, but also to a change in the deformation capabilities of the compressed concrete. In other words, the long-term strength of compressed concrete and its critical (limiting) deformations will depend not only on the class of the concrete itself but also on its strain rate.

The real modes of applying operating loads are actually quite long, therefore establishing similar dependencies between the parameters of compressed concrete will be important for building a universal model of concrete and reinforced concrete element and structure deformation.

This article is aimed at developing the key provisions of the general model of compressed concrete deformation under the action of long-term loads. The main task posed in this case is to establish the analytical dependence of the level of compressed concrete's long-term strength. It should provide a simple approach to considering the influence of long-term loading on the behaviour of compressed concrete both from the standpoint of its strength and its ability to maximally deform during the design of reinforced concrete elements and structures. The previously developed energy model (Romashko & Romashko, 2019a; Romashko & Romashko-Maistruk, 2022) can serve as the basis for such an approach, which is based on the general laws of preservation of the material's deformation potential energy under different modes of its loading.

MATERIAL AND METHODS

These studies are based on the most important laws of physical and mathematical modelling of the deformation processes of concrete and reinforced concrete elements and structures (Romashko & Romashko, 2019b; Romashko & Romashko, 2019c; Romashko, 2021) and the well-known law of the conservation of the specific potential energy of material deformation regardless of its loading mode.

Although Rüsch (1960) developed the first concept of concrete's long-term strength, he did not propose an analytical dependence on determining this strength. Later, Yashin (1969) attempted to solve this task, and later still, other researchers (Prokopovich, 1978; Bezgodov, 1996; Holovata et al., 2021; Raupov & Malikov, 2023) used a simple logarithmic dependence:

$$\eta_l = a - b \cdot \lg(t - t_0), \tag{1}$$

where:
a, b – empirical coefficients,
$(t - t_0)$ – load duration [days].

However, Function (1) is too primitive, as it does not consider the influence of a number of important technological and age factors, or the main concrete components, on its long-term strength.

Zaitsev (1972) proposed another dependence:

$$\eta(t, t_0) = \frac{m(t, t_0) \cdot R_c(t)}{R_c(t_0)} \cdot \sqrt{\frac{E(t_0)}{E(t)} \cdot \frac{1}{1 + E(t_0) \cdot C(t, t_0)}}, \tag{2}$$

where:
$\eta(t, t_0)$ – level of concrete's long-term strength,
$m(t, t_0)$ – function of the relative intensity of the surface energy of the fracture crack,
$R_c(t)$ – concrete's predicted strength at the time of its destruction $t \to \infty$ [MPa],
$R_c(t_0)$ – concrete's strength at the time of its loading [MPa],

$E(t_0)$, $E(t)$ – modulus of concrete's elasticity at the time of its loading and at the failure time, respectively [MPa],
$C(t, t_0)$ – measure of concrete creep.

The main disadvantage of Function (2) and its modifications (Ashrabov & Zaytsev, 1982; Krishan, Rimshin, Erofeev, Kurbatov & Markov, 2015; Raupov, Karimova, Zokirov & Khakimova, 2021) is that using it requires knowledge of the concrete's basic physical and mechanical characteristics at the age of 28 days, and at the times of its loading τ and probable destruction $t \to \infty$.

Further studies of compressed concrete's long-term strength (Awad & Hilsdorf, 1971; Stöckl, 1972; Ngab et al., 1981; Smadi et al., 1985; Han, 1996; Iravani & MacGregor, 1998) have been concerned not only with low- and medium-strength classes of concrete but also with high-strength concrete. The results of these studies have subsequently been reflected both in earlier and in current normative documents (Comité Euro-International du Béton [CEB], 1993; Fédération Internationale du Béton [FIB], 2013) with a more complex logarithmic-exponential dependence:

$$\eta_l = (0.96 - 0.12) \cdot \left(\ln\left(72\left(t - t_0\right)\right)\right)^{\frac{1}{4}} \cdot \exp\left(s\left(1 - \sqrt{\frac{28}{t_0}}\right)\right), \tag{3}$$

where:
η_l – level of concrete's long-term strength,
t_0 – concrete's age at the time of its loading [days],
s – coefficient depending on the cement class (R, N, S).

This dependence, although free of some of the above-mentioned disadvantages, is quite limited in use (Tasevski et al., 2018; Empelmann & Javidmehr, 2020).

Thus, considering all the above, it can be stated that research related to the resistance of compressed concrete to long-term loads will continue to be one of the most relevant topics in the general theory of reinforced concrete.

It is well known that such physical and mechanical characteristics of concrete as the compressive f_c and tensile f_{ct} strength and the corresponding critical strain ε_{c1} and ε_{ct1} largely depend on its strain rate. It is quite obvious that the lower the concrete's strain rate, the lower its strength will be and the greater will be the limiting (critical) concrete deformations at the moment of its destruction. At the same time, it is known that the product of the two above-mentioned parameters characterises the specific potential energy of the concrete's deformation. And, according to the law of conservation of potential energy, it should remain unchanged and independent of the loading mode of the material itself. In other words, the area of the compressed concrete strain diagram will remain constant or unchanged under any load type (Fig. 1).

In the case of instantaneous loading, the concrete will deform elastically, since plastic deformations or creep deformations will not have time to manifest themselves. Under such circumstances, the specific potential energy of the compressed concrete's deformation at the moment of its destruction can be calculated using a very simple expression (Romashko-Maistruk & Romashko, 2024):

$$u_d = \frac{f_{c,du}^2}{2E_{c0}}, \tag{4}$$

where:
E_{c0} – initial modulus of concrete elasticity under stress $\sigma_c = 0$ [MPa],
$f_{c,du}$ – strength of compressed concrete under instantaneous dynamic loading [MPa],
$\varepsilon_{c,du}$ – corresponding critical (limit) concrete strain under instantaneous dynamic loading.

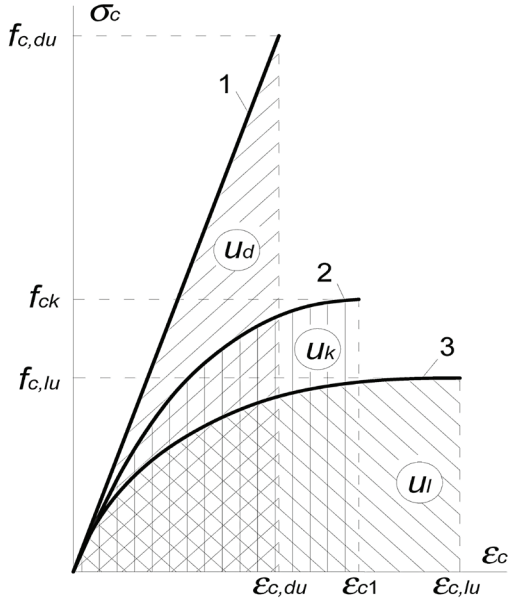


Fig. 1. Plots of specific potential energy of concrete destruction under loading: 1 – instantaneous dynamic; 2 – standardised short-term; 3 – long-term

Source: Romashko-Maistruk and Romashko (2024).

In the case of a short-term quasi-static mode of loading or deformation described by an incorrect fractional--rational function σ_c–ε_c (Romashko & Romashko, 2019b; Romashko, 2021), this energy should be calculated according to Romashko-Maistruk & Romashko (2024) by the expression:

$$u_k = \frac{dU}{dV} = \int_0^{\varepsilon_{c1}} \sigma_c d\varepsilon_c = \frac{f_{ck} \cdot \varepsilon_{c1}}{(k-2)} \left[-\frac{1}{2} + \frac{(k-1)^2}{(k-2)} - \left(\frac{k-1}{k-2} \right)^2 \cdot \ln(k-1) \right], \tag{5}$$

where:

k – characteristics of the compressed concrete's deformability ($k = E_{c0} \cdot \varepsilon_{c1} / f_{ck}$),

ε_c – compressed concrete's current strain,

f_{ck} – strength of the compressed concrete under the action of standardised static loads [MPa],

ε_{c1} – critical strain of the compressed concrete under the action of standardised static loads.

By a similar expression, it would be possible to determine the specific potential energy of compressed concrete's destruction under the long-term load action:

$$u_l = \int_0^{\varepsilon_{c,lu}} \sigma_c d\varepsilon_c = \frac{f_{c,lu} \cdot \varepsilon_{c,lu}}{(k_l-2)} \left[-\frac{1}{2} + \frac{(k_l-1)^2}{(k_l-2)} - \left(\frac{k_l-1}{k_l-2} \right)^2 \cdot \ln(k_l-1) \right], \tag{6}$$

where:

$f_{c,lu}$ – limit values of the long-term strength of the compressed concrete [MPa],

$\varepsilon_{c,lu}$ – corresponding critical strain of the compressed concrete,

k_l – characteristic of the compressed concrete's ultimate deformability under the action of long-term loads ($k_l = E_{c0} \cdot \varepsilon_{c,lu} / f_{c,lu}$).

However, the main parameters of this dependence, $f_{c,lu}$ and $\varepsilon_{c,lu}$ (as well as k_l), are unknown, and it is therefore practically impossible to determine the level of the concrete's long-term strength from the joint solution of Equations (5) and (6). However, from the joint solution of Equations (4) and (5), the dependence of the limit values of the compressed concrete's dynamic increase factor (DIF_u) was obtained (Romashko-Maistruk & Romashko, 2024):

$$DIF_u = \frac{f_{c,du}}{f_{ck}} = \sqrt{\frac{2k}{(k-2)}\left[-\frac{1}{2}+\frac{(k-1)^2}{(k-2)}-\left(\frac{k-1}{k-2}\right)^2 \ln(k-1)\right]}. \tag{7}$$

Function (7) characterises the ultimate strength of compressed concrete during its instantaneous deformation. With a decrease in the strain rate $\acute{\varepsilon}$, the dynamic increase factor will also decrease and will reach its minimum value at $\acute{\varepsilon} = 10^{-6}$ s^{-1} and equal the maximum possible level of compressed concrete's long-term strength, $DIF = \eta_l = 1$. This provides a single methodological approach to determining the compressive strength of concrete under any loading mode.

It is quite obvious that a further decrease in the level of compressed concrete's long-term strength will occur with a further decrease in its strain rate. With the help of numerical analysis methods, it was possible to link this process with the following dependence:

$$\eta_l = \frac{f_{c,lu}}{f_{ck}} = DIF_u^{\left(\frac{\left(\log\left(\frac{\acute{\varepsilon}}{\acute{\varepsilon}_s}\right)+1\right)}{9}\right)} \text{ for, } \acute{\varepsilon} \le 10^{-6} \text{ s}^{-1}, \tag{8}$$

where:
$\acute{\varepsilon}_s$ – maximum strain rate of compressed concrete under quasi-static loads ($\acute{\varepsilon}_s = 10^{-5}$ s^{-1}).

If the strain rate of compressed concrete is taken to be $\acute{\varepsilon} = 10^{-10}$ s^{-1}, according to Table 1, then its safe level of long-term strength can be calculated using the expression:

$$\eta_{lu} = DIF_u^{-\frac{4}{9}}. \tag{9}$$

Table 1. Compressed concrete strain rate depending on the load mode

Load mode	Strain rate ($\acute{\varepsilon}$) [s^{-1}]
Long ('creeping')	10^{-10}–10^{-6}
Static, quasi-static	10^{-6}–10^{-5}

Source: Romashko-Maistruk and Romashko (2024).

RESULTS

Formula (8) shows that compressed concrete's long-term strength depends not only on its physical and mechanical characteristics, reflected in DIF_u and the coefficient of elastic-plastic concrete's properties $k = E_{c0} \cdot \varepsilon_{c1}/f_{ck}$, but also on its strain rate, $\acute{\varepsilon}$. The first of these parameters is directly affected by the plastic properties (creep) of the concrete. The larger they are, the greater the elastic-plastic coefficient of the concrete

will be and the lower its long-term strength will be. In turn, the plastic properties of compressed concrete directly depend on its strain rate. Therefore, the lower the strain rate of the concrete, the lower its long-term strength will be. The calculations carried out fully confirmed the above. The values of the levels of compressed concrete's long-term strength, calculated according to Formula (8) for its different classes at different strain rates, are given in the Table 2.

Table 2. Levels of long-term compressive strength of concrete at different strain rates

Concrete class	Level of concrete long-term strength	
	η_l ($\acute{\varepsilon} = 10^{-8}$ s^{-1})	η_{lu} ($\acute{\varepsilon} = 10^{-10}$ s^{-1})
C8/10	0.794	0.630
C12/15	0.808	0.654
C16/20	0.823	0.678
C20/25	0.835	0.697
C25/30	0.845	0.714
C30/35	0.854	0.730
C32/40	0.863	0.744
C35/45	0.869	0.756
C40/50	0.878	0.77
C45/55	0.884	0.782
C50/60	0.890	0.793
C53/65	0.896	0.803
C56/70	0.901	0.813
C60/75	0.907	0.823
C65/80	0.912	0.831
C70/85	0.916	0.839
C75/90	0.921	0.848
C80/95	0.924	0.854
C85/100	0.928	0.862
C90/105	0.932	0.868
C95/110	0.935	0.874
C100/115	0.939	0.881
C105/120	0.941	0.886

Source: authors' compilation.

DISCUSSION

It is apparent that the dependence of the main physical and mechanical characteristics of concrete on its strain rate can be applied to a general model of concrete deformation. One of the first to draw attention to this was Rüsch (1956, 1960). However, most of the functions of compressed concrete's long-term strength known today, which are obtained mainly empirically, do not reflect any analytical connection with its strain rate. In addition, these functions were determined to be completely independent of the class of the concrete itself. This is true even though it is very apparent that the level of plastic deformation, and therefore the level of long--term strength of a compressed concrete, directly depends on both its class and strain rate.

The peculiarity of Function (8) is that it is free of the above-mentioned disadvantages, since it was obtained analytically within the framework of a single methodological approach to predicting the strength of any class compressed concrete at any strain rate (Fig. 2).

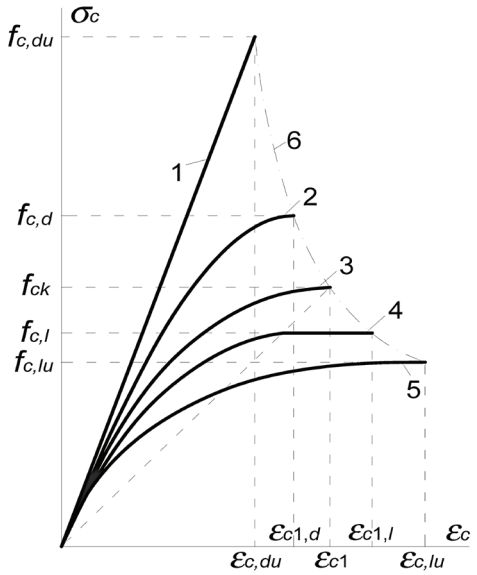


Fig. 2. Diagrams of compressed concrete deformation under different types and modes of loading: 1 – instantaneous; 2 – dynamic; 3 – short-term; 4 – long-term; 5 – extremely long-term; 6 – curve of limit deformations

Source: authors' compilation.

In order to evaluate the effectiveness of the developed method for determining the level of compressed concrete's long-term strength, the results of theoretical calculations according to expression (8) were compared with individual researchers' experimental data. All of them are displayed in Figure 3 and confirm that the lower limit of a compressed concrete's long-term strength should be predicted according to dependence (9).

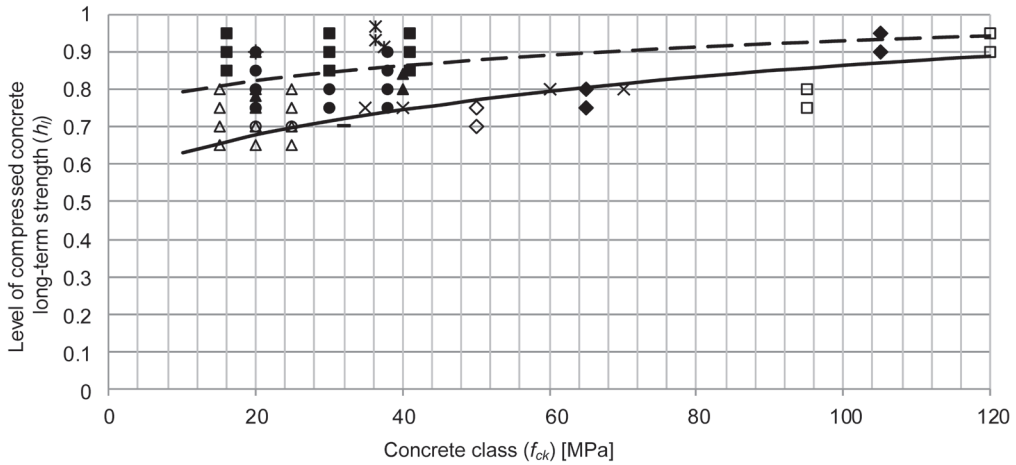


Fig. 3. Long-term strength of compressed concrete according to the results: of experiments with destroyed samples (▲ – Graf & Brenner, 1937; + – Shank, 1949; ● – Rüsch, 1956; ■ – Awad & Hilsdorf, 1971; × – Smadi et al., 1985; ◆ – Iravani & MacGregor, 1998; ✱ – Tasevski et al., 2018) and with unbroken samples (– – Sell, 1959; △ – Yashin, 1969; ◇ – Stöckl, 1972; ○ – Smadi et al., 1985; □ – Iravani & MacGregor, 1998); calculations according to Formula (8) at strain rates ——— – $\dot{\varepsilon} = 10^{-10}$ s^{-1} and — — — – $\dot{\varepsilon} = 10^{-8}$ s^{-1}

Source: authors' compilation.

CONCLUSIONS

The previously developed provisions and hypotheses of the energy model of concrete and reinforced concrete deformation confirm that:

– the foundations of the general model of concrete deformation under the action of long-term loads have been formed,
– for the first time, an analytical relationship has been proposed that links the level of compressed concrete's long-term strength not only with its defining elastic-plastic standardised characteristics under the action of short-term loads $k = E_{c0} \cdot \varepsilon_{c1}/f_{ck}$, but also with the concrete's strain rate $\acute{\varepsilon}$,
– the resulting dependence makes it possible to control the entire process of compressed concrete deformation in concrete and reinforced concrete elements and structures under the action of long-term loads and predict the level of its long-term strength.

In general, the above research results open up wide opportunities in the development of a universal calculating method of reinforced concrete elements and structures under any duration of the action of loads.

REFERENCES

Ashrabov, A. A. & Zaytsev, Y. V. (1982). *Elements of fracture mechanics of concrete*. Tashkent: Ukituvchi.

Awad, M. E. & Hilsdorf, H. K. (1971). *Strength and Deformation Characteristics of Plain Concrete Subjected to High Repeated and Sustained Loads*. Urbana, IL.: University of Illinois at Urbana-Champaign. Retrieved from https://www.ideals.illinois.edu/items/14427

Bezgodov, I. M. (1996). O dlitelnoi prochnosti betona [About the long-term strength of concrete]. *Beton i zhelezobeton*, *4*, 23–25.

Comité Euro-International du Béton [CEB], (1993). *CEB-FIP Model Code 1990. Design code* (CEB-FIP MC 1990). London: Thomas Telford Ltd. Retrieved from http://www.tocasa.es/zona2/CEB_FIP_model_code_1990_ing.pdf

Empelmann, M. & Javidmehr, S. (2020). Evaluation of concrete compression failure under high sustained loads. *Proceedings of the fib Symposium*, *22*, 827–834.

Fédération Internationale du Béton [FIB], (2012). *Model Code 2010. Final draft*. Vol. 2 (FIB MC 2010). Lausanne: Federal Institute of Technology (EPFL). Retrieved from https://vdoc.pub/download/fib-66-model-code-2010-final-draft-volume-2-122qcq34ikio

Graf, O. & Brenner, E. (1937). Versuche mit Betonkörpern, die einer dauernd wirkenden Druckbelastung ausgesetzt waren. *Bauingenieur*, *19/20*, 237–270. Retrieved from http://delibra.bg.polsl.pl/Content/23272/BCPS_24910_1937_Der-Bauingenieur-19.pdf

Han, N. (1996). *Time Dependent Behaviour of High Strength Concrete* (doctoral thesis). Delft University of Technology, Delft. Retrieved from https://repository.tudelft.nl/record/uuid:ab8b4cfa-0c72-4e84-8d17-f5841715972e

Holovata, Z., Neutov, S. & Surianinov, M. (2021). Modeling of the stress-strain state of reinforced concrete beams under prolonged load action. *IOP Conference Series: Materials Science and Engineering*, *1162*, 012004. https://doi.org/10.1088/1757-899X/1162/1/012004

Iravani, S. & MacGregor, J. G. (1998). Sustained load strength and short-term strain behavior of high-strength concrete. *ACI Materials Journal*, *95* (5), 636–647.

Krishan, A., Rimshin, V., Erofeev, V., Kurbatov, V. & Markov, S. (2015). The Energy Integrity Resistance to the Destruction of the Long-Term Strength Concrete. *Procedia Engineering*, *117*, 211–217. https://doi.org/10.1016/j.proeng.2015.08.143

Ngab, A. S., Slate, F. O. & Nilson, A. H. (1981). Microcracking and Time-Dependent Strains in High Strength Concrete. *ACI Journal*, *78*, 262–268. https://doi.org/10.14359/6923

Prokopovich, I. E. (1978). *Osnovi prikladnoi lineinoi teorii polzuchesti* [*Fundamentals of applied linear theory of creep*]. Kyiv: Vyshcha shkola.

Raupov, C. & Malikov, G. (2023). Creep in expanded clay concrete at different levels of stress under compression and tension. *E3S Web of Conferences*, *365*, 02008. https://doi.org/10.1051/e3sconf/202336502008

Raupov, C., Karimova, A., Zokirov, F. & Khakimova, Y. (2021). Experimental and theoretical assessment of the long-term strength of lightweight concrete and its components under compression and tension, taking into account the macrostructure of the material. *E3S Web of Conferences*, *264*, 02024. https://doi.org/10.1051/e3sconf/202126402024

Romashko, V. M. (2021). General model and the mechanics of concrete elements and structures deformation. *IOP Conference Series: Materials Science and Engineering*, *1021*, 012026. https://doi.org/10.1088/1757-899X/1021/1/012026

Romashko, V. & Romashko, O. (2019a). Energy resource of reinforced concrete elements and structures for the deformation-force model of their deformation. *IOP Conference Series: Materials Science and Engineering*, *708*, 012068. https://doi.org/10.1088/1757-899X/708/1/012068

Romashko, V. & Romashko, O. (2019b). Fundamentals of the General Theory of Resistance of Reinforced Concrete Elements and Structures to Power Influences. *Materials Science Forum*, *968*, 534–540. https://doi.org/10.4028/www.scientific.net/MSF.968.534

Romashko, O. & Romashko, V. (2019c). Model of multilevel formation of normal cracks in reinforced concrete elements and structures. *IOP Conference Series: Materials Science and Engineering*, *708*, 012069. https://doi.org/10.1088/1757-899X/708/1/012069

Romashko, V. & Romashko-Maistruk, O. (2022). Strength resource calculation of the reinforced concrete elements according to the energy criterion. *Procedia Structural Integrity*, *36*, 269–276. https://doi.org/10.1016/j.prostr.2022.01.034

Romashko-Maistruk, O. & Romashko, V. (2024). Model of concrete deformation under the action of dynamic loads. *Procedia Structural Integrity*, *59*, 352–359. https://doi.org/10.1016/j.prostr.2024.04.050

Rüsch, H. (1956). Versuche zur Bestimmung des Einflusses der Zeit auf Festigkeit und Verformung [Experiments to Determine the Influence of Time on Strength and Strain]. *IABSE Kongressbericht*, *5*, 237–244. Retrieved from https://www.e-periodica.ch/digbib/view?lang=de&pid=bse-cr-001%3A1956%3A5%3A%3A1584#1585

Rüsch, H. (1960). Researches Toward a General Flexural Theory for Structural Concrete. *ACI Journal*, *57* (1), 1–28. Retrieved from http://www.phd.eng.br/wp-content/uploads/2014/06/ar0.pdf

Sell, R. (1959). Investigation into the Strength of Concrete Under Sustained Load. *RILEM Bulletin*, *5*, 1–13.

Shank, J. R. (1949). Plastic Flow of Concrete at High Overload. *ACI Journal*, *45* (2), 493–498. https://doi.org/10.14359/12157

Smadi, M. M., Slate, F. O. & Nilson, A. H. (1985). High-, Medium-, and Low-Strength Concretes Subject to Sustained Overloads – Strains, Strengths, and Failure Mechanisms. *ACI Materials Journal*, *82* (5), 657–664. https://doi.org/10.14359/10376

Stöckl, S. (1972). Strength of Concrete under Uniaxial Sustained Loading. *SP-34 Concrete for Nuclear Reactors*, *1*, 313–326.

Tasevski, D., Fernández, Ruiz M. & Muttoni, A. (2018). Compressive Strength and Deformation Capacity of Concrete under Sustained Loading and Low Stress Rates. *Journal of Advanced Concrete Technology*, *16*, 396–415. https://doi.org/10.3151/jact.16.396

Yashin, A. V. (1969). Deformatsii betona pod dlitelnim vozdeistviem visokikh napryazhenii i yego dlitelnoe soprotivlenie pri szhatii [Deformation of concrete under prolonged exposure to high stresses and its long-term compressive resistance]. In A. A. Gvozdev (Eds), *Osobennosti deformatsii betona i zhelezobetona i ispolzovanie EVM dlya otsenki ikh vliyaniya na povedenie konstruktsii* (pp. 38–76). Moskva: Stroiizdat.

Zaitsev, Yu. V. (1972). Razvitie treshchin v tsementnom kamne i betone pri kratkovremennom i dlitelnom szhatii [Development of cracks in cement stone and concrete under short-term and long-term compression]. *Beton i zhelezobeton*, *11*, 41–43.

Romashko-Maistruk, O. (2025). Predicting long-term strength of compressed concrete. *Acta Sci. Pol. Architectura*, *24*, 60–69, DOI: 10.22630/ASPA.2025.24.5

PROGNOZOWANIE DŁUGOTRWAŁEJ WYTRZYMAŁOŚCI BETONU ŚCISKANEGO

STRESZCZENIE

Tematem artykułu jest charakterystyka cech odkształceń betonu ściskanego pod wpływem obciążeń długotrwałych. Celem badań, zaprezentowanych w artykule, było ustalenie zależności analitycznej na określenie poziomu wytrzymałości długotrwałej betonu ściskanego. Zastosowano hipotezę niezmienności i niezależności od sposobu obciążenia betonu konkretnej energii potencjalnej jego ostatecznego odkształcenia (zniszczenia). Dzięki krytycznej analizie prac innych badaczy uzyskano zależność funkcyjną poziomu wytrzymałości długotrwałej betonu ściskanego nie tylko od jego znormalizowanych charakterystyk sprężysto-plastycznych, lecz także od szybkości odkształcenia betonu. Ocenę proponowanej metodyki określania poziomu wytrzymałości długotrwałej betonu ściskanego sprowadza się do porównania odpowiednich wyników obliczeń teoretycznych z opublikowanymi danymi eksperymentalnymi różnych badaczy.

Słowa kluczowe: beton, model energetyczny, właściwa energia potencjalna, szybkość odkształcenia, poziom wytrzymałości długotrwałej

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A CRITICAL REVIEW OF THE IMPLEMENTATION OF BUILDING INFORMATION MODELLING (BIM) IN CONSTRUCTION PROCESSES IN POLAND: DEEP INSIGHTS

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ABSTRACT

The increasing digitisation of the construction industry is generating global interest in building information modelling (BIM) methodology. Recognising the tangible benefits it brings, many countries are choosing to begin work on implementing the so-called mandate, defining national implementation plans and introducing legal regulations. The purpose of this article was to conduct an in-depth study and literature search on the current state of BIM implementation in Poland. As part of a structured implementation of the work, the previous activities of central government bodies towards the so-called BIM mandate were examined. The ongoing optionality of BIM application in public procurement is shown, as well as the lack of coordinated top-down activities, as they play a major role towards national implementation. In addition, the relevance of NGO activities in the process of popularising BIM was presented. As a result of the critical analysis, an assessment and discussion of the possible future directions of BIM implementation in Poland was made.

Keywords: building information modelling, BIM mandate, implementation, adoption, construction process

INTRODUCTION

Digital technologies are having a significant impact on the development and shaping of various sectors of the economy, including the construction industry. Influenced by the rapidly changing market and its needs, construction information is becoming an even more valuable resource than ever. As demand increases, the change is to be provided by the building information modelling (BIM) concept. The concept, which accompanies the entire life cycle of a building, introduces fundamental changes to the entire existing philosophy of the property development and construction process. It refers to new technology for information modelling and a process that provides tangible benefits for all players and areas in the architecture, engineering, and construction (AEC) industry. Developments resulting from the digitisation of the construction industry and the need to guarantee a higher quality of information have generated global interest in a methodology that changes the entire previous approach to the implementation of a construction project.

Many countries have begun to recognise the potential of BIM, and therefore, work on its implementation has begun, defining national implementation plans and introducing appropriate regulations. As a result, different

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approaches to supporting the process have been formed, such as recommendations for the use of BIM (optional approach) and provisions for mandatory supplementation of the contract with the use of the methodology in the procurement (mandatory approach). Among the leaders in the use of BIM are countries such as the United States, Australia, the United Kingdom, and Singapore. The multi-year strategies drawn up by the countries, the pilot programmes conducted, and the standards developed still serve as a model and basis for BIM adoption in other public sectors around the world. Significantly, the public sector is cited as a key initiator and overseer of the implementation and promotion of BIM among stakeholders (Cheng & Lu, 2015).

Development work commissioned by government agencies that includes any study and analysis of the feasibility of implementing BIM at the national level is referred to as top-down activities. By design, they are intended to lead to mandatory use of BIM in procurement. Currently, 29% of European countries have or plan to make either full or partial provisions for mandatory use of the methodology in public procurement. In contrast, 6% require or will require BIM in contracts in selected public institutions (Mitera-Kiełbasa & Zima, 2024a). The national implementation process meets broad and multi-level support to cover the entire construction market systematically, including at the international level. An equally important task is to effectively raise interest among more potential users of the methodology. The international expansion of BIM is taking place, regardless of whether the national level is interested in the methodology or not. Therefore, with time, a grassroots initiative is also being singled out. This includes any activity related to the adoption of BIM for the internal needs of the company and includes ongoing educational tasks. Bottom-up activities drive top-down activities, and in the case of Poland, they play a particularly important role. On the other hand, compared to other equally developed markets around the world, Poland still has not implemented the mandatory use of BIM methodology in public procurement. The plans developed so far, as well as the prospect of introducing the methodology from 2025 to contracts with a minimum value, might be a vision that is highly likely to be postponed, resulting in a process that will continue to remain at a working stage. Although against the background of Central and Eastern Europe, implementation work is not undertaken in countries virtually at all, the Czech Republic is an example of a country with a similar level of GDP to Poland; the first BIM mandate was introduced in 2023.

MATERIAL AND METHODS

The execution of the work was based primarily on literature research by evaluating and validating existing content. The basis of the study was the compilation of all events and initiatives related to BIM in Poland in absolute chronological order, and this, in turn, allowed us to proceed to the next stages of the research (Fig. 1).

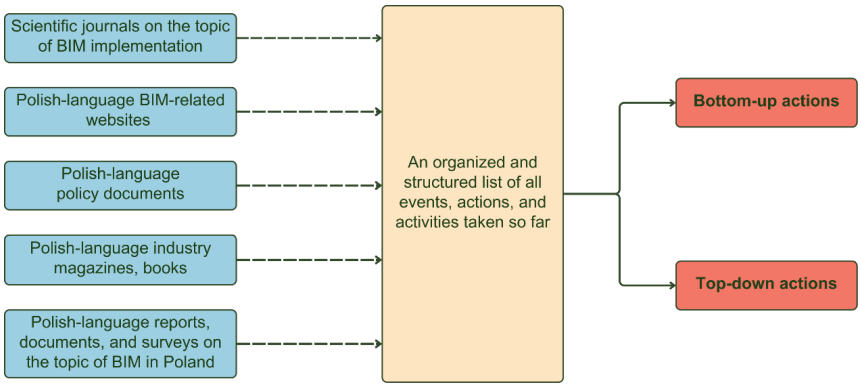


Fig. 1. Research workflow

Source: own work.

The study identified all parties, actors, participants and stakeholders influencing the implementation of BIM in Poland. A reliable check of the bottom-up and top-down activities carried out made it possible to determine the events that have a particular impact on raising awareness in the context of using BIM in the property development and construction process. From the scope of grassroots activities, the most relevant sections were identified, and their topics were discussed and evaluated, and the relevance of their further implementation was argued. Domestic activities were analysed from the legal point of view and in terms of the general interest of government institutions in the subject matter undertaken. The entire article was subjected to observations, reflections, and considerations, and it was topped off with an element of discussion and consideration of the future of the methodology's implementation in Poland.

RESULTS

Grassroots activities

In Poland, it is undoubtedly fundamental to spread the knowledge gained from the implementations among practitioners, primarily through grassroots initiatives. In addition to the associations of architects or civil engineers that have been in existence for more than a dozen years, organisations have also begun to emerge whose guiding purpose is to support and educate strictly in the BIM methodology. This is even more important because the direction set by the pioneers of the BIM concept taken up in Poland resulted in the need for more potential implementing companies to rely on their experience. The demand for education and further qualifications of current and future designers from the use of the new technology was high, and the training opportunities were limited. The beginning of the 2010s was still dominated by training courses organised by partners of software vendors (Anger, Laguna & Zamara, 2021). It can be said that the awareness built up even though the very definition of BIM was limited to understanding it only in terms of new applications and technological innovation in construction, which is expected to bring certain benefits. There have also been cognitive errors in the context of BIM implementation, such as if it is only a concept meant for large companies and large-scale developments or if the moment for implementation is still too early (Miecznikowski, 2014d).

The activities leading to the consolidation and systematisation of the idea of BIM in Poland can be reduced to one slogan – education. In turn, it can be further expanded to include publications, conferences, trade fairs, meetings, debates, training, courses, workshops, lectures, presentations, seminars, research and development, guides, certification, books, manuals, industry blogs or support in starting new majors and specialities at universities. The grassroots initiative just carried out was and still is a fundamental factor in the drive to digitise the Polish construction industry and push forward national activities, which are still scarce. The earliest publications were already based on the popularisation of the paradigm and identified the need for further development of methodology and technology with the participation of, among others, standards bodies and legislative bodies (Miecznikowski, 2013). Moreover, several well-conducted foreign implementations in countries such as the United Kingdom, the United States, Ireland, and the Scandinavian countries were strongly pointed out, which can provide a source of proven practices and be the basis for applying the BIM requirement in Poland as well (Dorna & Glema, 2016; Mitera-Kiełbasa & Zima, 2024b). On the other hand, seeing insufficient response from the national level, experts began to use the experience gained primarily by directing all activities to the main potential audiences and users of the methodology. In the pursuit of digital transformation, the main goal is to reach the most interested parties, raise awareness, and teach and share the current state of knowledge. Hence, existing and emerging organisations and associations have begun to adapt to the changing market, setting further or new guiding objectives for their activities.

According to Figure 2, the organisations formed in the first years of the 21st century mainly resulted from economic growth and the need to support and protect the professional interests of members in terms of changing laws, joining the European Union and the requirement to comply with EU standards, as well as the generally

resulting need to professionalise the construction industry in Poland. One can observe a confirming relationship between any major contact with the concept of modelling information about a building and the resulting need for education in Poland in the 2010s. At that time, organisations were formed that brought together companies and people primarily associated with BIM – the BIM Cluster, the BIM Association, the ECC BIM Foundation, and the Polish branch of the buildingSMART Association.

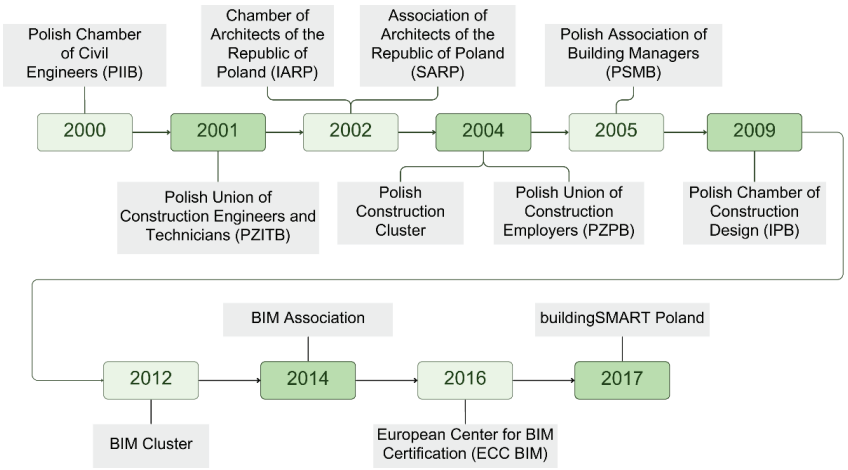


Fig. 2. NGOs working on grassroots initiatives for the development of BIM methodology in Poland

Source: own work.

As a grassroots initiative, various collaborations were established between organisations, and teams were set up to enforce the set goals and objectives for the implementation of BIM in Poland (Fig. 3).

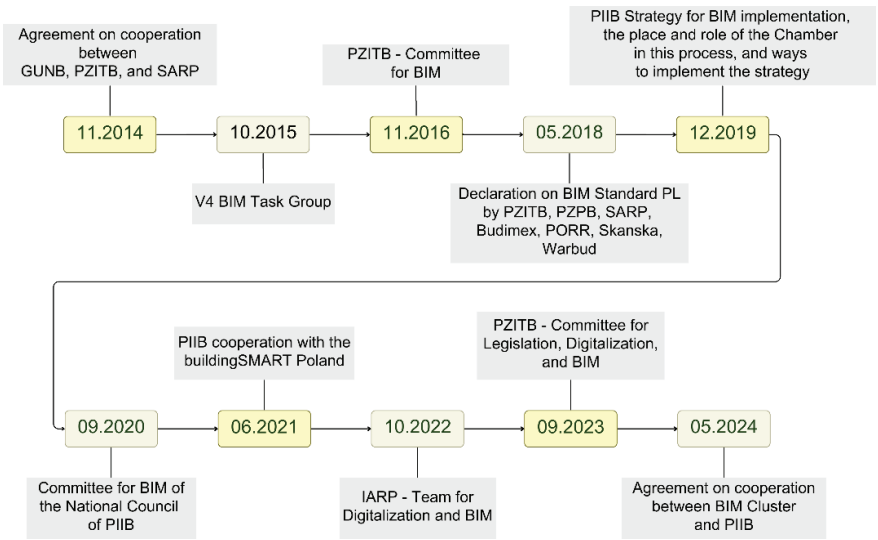


Fig. 3. Important initiatives leading to the popularisation and shaping of BIM methodology in Poland

Source: own work.

One of the first and most significant agreements was the cooperation established in 2014 between the Polish Association of Construction Engineers and Technicians (in Polish: *Polski Związek Inżynierów i Techników Budownictwa* – PZITB), the Association of Polish Architects (in Polish: *Stowarzyszenie Architektów Polskich* – SARP), and the Chief Inspector of Building Supervision (in Polish: *Główny Urząd Nadzoru Budowlanego*). The last page of the agreement is particularly significant, as an agreement was signed on behalf of the government and is seemingly much closer to the digitisation of the construction process, especially in terms of adjusting the Public Procurement Law. The agreement was about strengthening cooperation, as well as giving opinions and pointing out inaccuracies in the provisions of acts and regulations (Inspektorat Nadzoru Budowlanego, Polski Związek Inżynierów i Techników Budownictwa & Stowarzyszenie Architektów Polskich [INB, PZIiTB, SAP], 2014). In turn, a specially appointed team of experts set a framework for action and recommendations for the process of BIM implementation in ongoing public procurement (Anger, Lisowski, Piwkowski & Wierzowiecki, 2015). Defining such tasks is extremely important to make all stakeholders aware of the necessary amount of work that needs to be done to gradually move towards the jointly set goal. Shortly thereafter, the main result of the cooperation was the creation of the V4 BIM Task Group, an ambitious concept involving the Visegrad Group countries, which was to participate in the drafting of recommended standards (Ustinovičius, Wierzowiecki & Puzinas, 2016) and the development of a BIM education programme (Piwkowski, 2017). In contrast, there have been virtually no more significant group activities since 2016. Another major declaration of cooperation was an agreement between NGOs (PZiTB, PZPB, SARP) and companies from the construction industry (Budimex, PORR, Skanska, Warbud) in the context of developing a BIM document called BIM Standard PL. The draft and its appendices were published in 2020. The manual is a set of proposals and recommendations on the preparation and implementation of BIM methodology in construction projects, in the creation of which the Public Procurement Office (in Polish: *Urząd Zamówień Publicznych* – UZP) also participated. In addition to the tangible effects of cooperation, internal activities of associations and clusters should also be identified as important developments. Particularly in recent years, there has been a noticeable increase in the number of established committees, teams, and published action plans among basically all associations. Starting with the strategy of the Polish Chamber of Civil Engineers (in Polish: *Polska Izba Inżynierów Budownictwa* – PIIB), where the postulate was to define the direction of implementation of the established goals in the field of digitisation of the construction process, legislation, standardisation, and popularisation of BIM. The Chamber pledged to be active in virtually all areas of work on the implementation of the methodology. The drafted document presents conclusions on the scope of activities to date and identifies challenges and risks arising from the BIM implementation process (Polska Izba Inżynierów Budownictwa [PIIB], 2019). Similar goals are being addressed by the following task forces that have been formed: the BIM Committee (which implements the Polish Chamber of Civil Engineers Strategy), the Digitisation and BIM Team (IARP), the Committee on Legislation, Digitisation and BIM (PZITB) and the committees operating in the district chambers. The growing number of these bodies indicates that the coordination of inter-agency cooperation activities is intensifying. Cooperation undertaken between organisations gives the opportunity to mutually spread the most up-to-date knowledge, along with greater opportunities for undertakings in the direction of popularisation of the methodology. Therefore, for example, the buildingSMART Association supports this process based on the continuous development of open communication standards, and in cooperation with the Polish Chamber of Civil Engineers, it is possible to disseminate the openBIM approach, at least in trade journals (Rydzy, 2021). Another important milestone is the initiative carried out by the ECC BIM foundation concerning the translation of the multi-part standard PN-EN ISO 19650 (Magiera, Czaplejewicz, & Wala, 2021), which was completed in 2024.

A component of the tasks carried out is also taking part in organised events. Representatives of companies and industry specialists promote the implementation of the methodology in speeches, lectures, talks, and workshops, as well as discussions of various case studies. The first time the topic of building information

modelling appeared at a conference was in 2012. Certainly, in the first years, from among the main organisers one can point to software manufacturers and vendors and their partners (including Autodesk, Graphisoft, WSC, Procad, MAT IT Services) on occasion promoting applications and tools dedicated to designers. Focusing only on selling a product to improve the design process may have overlooked the true idea of BIM, especially in the first editions. Many of them were one-off events dedicated to BIM technology. As time went on, there were more and more related threads, and gradually, conferences devoted entirely to BIM methodology began to be implemented on a national level. Of such organisers, one can mention the BIM Cluster or the ECC BIM Foundation, among others, and thanks to cooperation with an experienced background of specialists, it is now standard that part of the programme involves presenting the directions in which BIM is heading – the idea of a digital twin or expansion to other systems and technologies. Moreover, most events are held periodically, at least once a year, and those shown in Figure 4 systematically continue in subsequent years. The popularity of the conferences also brings together representatives of foreign companies sharing international practices and experiences. In turn, participants are provided an opportunity to update or supplement their knowledge and to expand their contacts with other BIM enthusiasts, users, and beneficiaries.

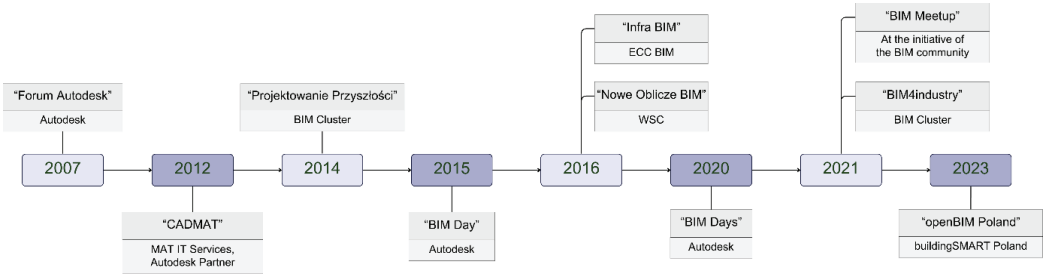


Fig. 4. First editions of conferences devoted to BIM methodology in Poland, along with their organisers

Source: own work.

Upgrading BIM skills in Poland is an indispensable part of the topics of discussion and plans for the organisation's strategy (PIIB, 2019). This applies to retraining incumbent workers and educating those at the secondary and higher education stages. The work on implementation and the need to ensure high-quality education is included, among others, in a project called BIM Education on the initiative of the Polish Association of Construction Engineers and Technicians (part of the V4 BIM Task Group), where there is a commitment in all state technical universities to introduce a uniform core curriculum with BIM included (Piwkowski, 2017). Other associations that participate in the organisation of BIM methodology classes are also members of the ECC BIM Foundation or the BIM Association. The development of an educational programme and support for educating future designers, engineers, and professionals who will be exposed to the BIM methodology is a key procedure to carry out effective and synergistic implementation of BIM in Poland. To chronologically organise the activities undertaken, the graphic (Fig. 5) lists: the first taught subject on BIM technology, the first BIM specialisation, the first BIM postgraduate courses offered at public and private universities, the unified core curriculum on BIM teaching, and the first BIM course in first- and second-level studies. It is worth mentioning that the last two items mentioned in the list are in the Integrated Qualifications Register (in Polish: *Zintegrowany Rejestr Kwalifikacji*) (Zintegrowany Rejestr Kwalifikacji [ZRK], n.d.). Currently, several BIM-related majors have been launched at universities, offering both practical and theoretical education, and the course offerings also include expanded material to include human resource management and business psychology (Mazovian OIIB, n.d.).

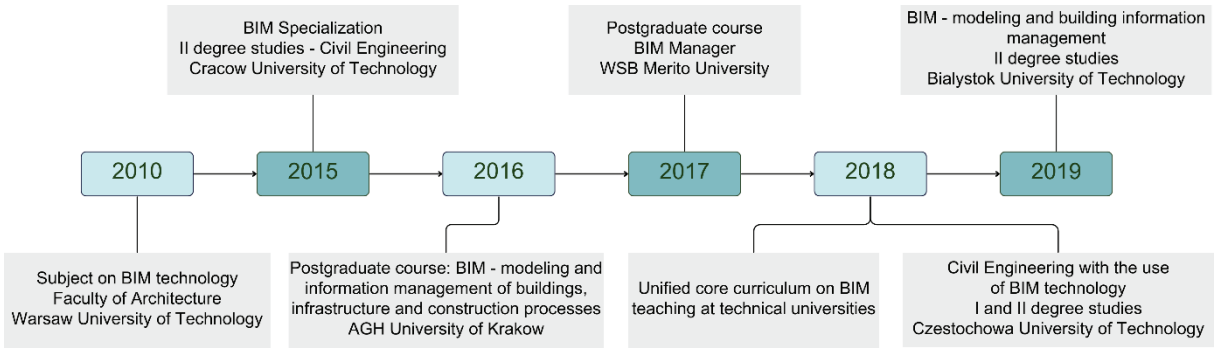


Fig. 5. First initiatives at universities for BIM education in Poland

Source: own work.

The published manuals were intended to be repositories of knowledge on which students and users of the methodology were to base their knowledge. The first Polish edition was published in 2015. According to the educational plan of universities, the first and, at the same time, the most important publications were supposed to fulfil the task of the main literature item (Piwkowski, 2017). On the other hand, they appeared infrequently (Fig. 6). The most necessary information contained in them includes: a discussion of the difference between CAD technology and BIM, dimensions and maturity levels of BIM, the idea of open standards, implementation of BIM in a construction project, and further prefixes for information modelling (Tomana, 2016; Kasznia, Magiera & Wierzowiecki, 2018).

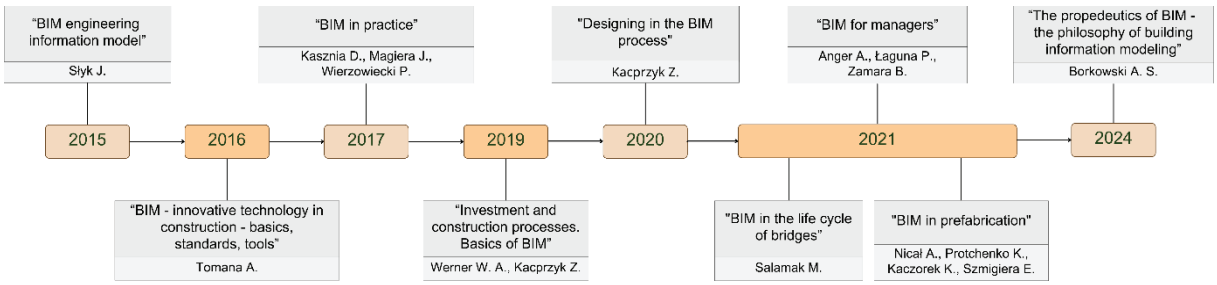


Fig. 6. Polish editions of books discussing building information modelling

Source: own work.

Over time, works have begun to describe BIM more broadly: for specific industries, from the perspective of the role occupied in combination with subsequent systems, and identifying the development trends of the methodology (Salamak, 2021). Undeniably, there are few Polish books on the subject. From the content of the published books, it can be concluded that the topics covered in them are mostly established textbook knowledge with little variation – even more reason for this in the case of the current situation in Poland regarding the application of BIM methodology in the property development and construction process. In contrast, more tailored and up-to-date publications can be found in blog entries at (BIM blog, n.d.; BIM4u.eu, n.d.).

Optional approval of the use of BIM

By 2014, interest in the BIM methodology was gradually growing within individual enterprises. The first construction projects using BIM were also observed. Grassroots activities successfully began to be accentuated in many areas, such as in the topics taken up at conferences, among others. On the other hand, no matter how optimistic the vision of promoting the almost inevitable change in the construction industry and the resulting development work for BIM methodology in Poland, it was alarming that these activities were insufficient (Miecznikowski, 2014a). This was particularly highlighted in situations where uncoordinated marketing efforts by software partners were an element that made it extremely difficult to build awareness of the methodology properly. Moreover, the rapid and haphazard introduction of technology along with the belief that investing in software would be a sufficient step to increase process efficiency, among other things, was another of the many cognitive errors mentioned. Therefore, the necessary work was also carried out from the bottom-up in terms of obviously promoting the functionality of the application, but also spreading the much greater benefits carried by the assumptions of BIM (Olszewski, 2013). In addition to this, this period also saw the presentation of BIM Vision, a Polish browser application widely known in the market today, giving designers another basis for realising a project not only for individual needs (open IFC format), along with cost estimation in BIMestiMate (Zima & Leśniak, 2013).

The work done undoubtedly laid a solid foundation for further development, so it was even more important to arouse interest in BIM at the government level. This was especially warranted when observing foreign implementations at the national level, which at that time had either defined a clear framework for implementing the methodology or were already maturely applying it. It is not without reason that 2014, above all, was marked by an optimistic outlook for increased involvement of the domestic side. The basis for the actions taken in the next 10 years in Poland is the adopted European directive of 24 February 2014 to recommend the use of electronic construction data modelling tools in public procurement: 'For public works contracts and competitions, Member States may require the use of specific electronic tools, such as electronic construction data modelling tools or similar. [...]' (Article 22, Paragraph 4 of Directive 2014/24/EU).

The adopted Second Directive 2014/25/EU on procurement by entities operating in the water, energy, transport, and postal services sectors also contains the same provision (Directive 2014/25/EU). The directive gave member states a choice in deciding whether to use technology in public procurement. Implicit in this provision is the issue of allowing the use of BIM methodology on an optional basis. At the start of 2014, the direction towards which the Polish government would, in principle, head was given, and an opportunity to accelerate national action also arose. Therefore, special attention should be paid to the first months after the publication of the directive, analysing the observed activities as well as the government's overall approach to the matter of implementing the methodology at the national level, even more so because the issue of structuring the implementation of BIM into an appropriate framework for action involves many players and requires cooperation among them. Hence, we can distinguish (according to the current naming of offices): the Ministry of Development and Technology (in Polish: *Ministerstwo Rozwoju i Technologii* – MRiT) – including the Public Procurement Office (in Polish: *Urząd Zamówień Publicznych*), which is subordinate to it – together with the Department of Architecture (in Polish: *Departament Architektury*), Construction and Geodesy; the Ministry of Infrastructure (in Polish: *Ministerstwo Infrastruktury* – MI); and the Ministry of Science and Higher Education (in Polish: *Ministerstwo Nauki Szkolnictwa Wyższego* – MNiSW), together with central administrative bodies supervised by the mentioned ministries, among others. In addition to this, it is necessary to determine the extent to which the methodology has been used in construction projects carried out at the time and to check the presence of a possible provision in public procurement. The distinguished components that played the most important role after the publication of Directive 2014/24/EU are shown in Figure 7.

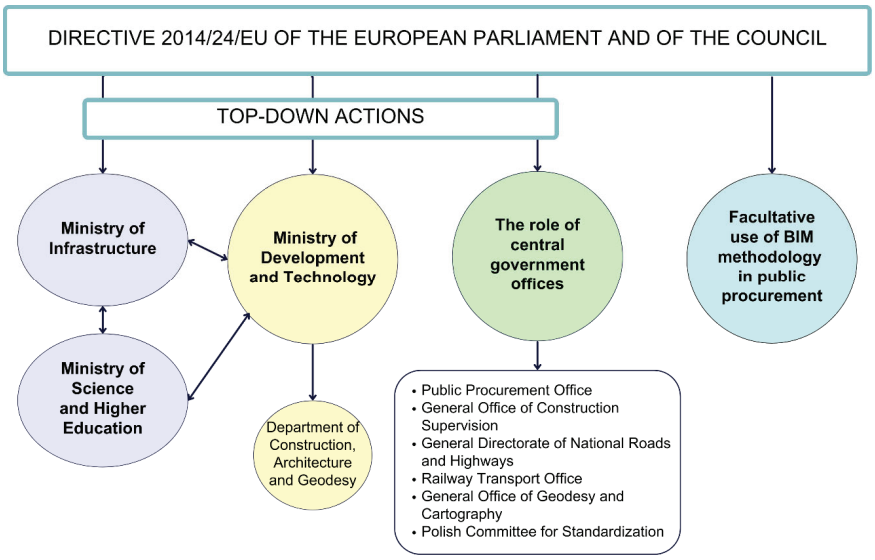


Fig. 7. Activities and actors integral to the implementation of the BIM methodology in Poland after the publication of Directive 2014/24/EU in the following years

Source: own work.

Expectations for defining a national stance on BIM implementation were high from the very beginning. Therefore, it should be emphasised that the popularisation process of BIM was quite quickly connected directly with the practice in the UK, among other things because of the Association of Polish Engineers and Technicians operating there. The consultations that were carried out created many opportunities to take up the topic of implementation or minimal familiarisation with the new approach to the construction project in progress. On the other hand, none of the representatives of public sector clients were interested (Miecznikowski, 2014b). In addition to this, it was possible to get to know from the very beginning a rather clear approach to the topic of the direct relationship between public procurement and the better quality of the delivered product, for example, during one of the debates at the conference held in April 2014. The issue of political image and the awarding of public procurement with minimal legal risk was put forward over a long--term and strategic approach to the property development and construction process, and the essence of public procurement in general, which should be carried out on the basis of higher goals, if only for the sake of future users (Miecznikowski, 2014c). The European directive, along with the use of electronic tools, describes issues inherent in the BIM concept, such as the entire life cycle of a building and with it the essential criterion for public procurement, which is the criterion of the offer with the best value for money (and not the lowest price as before). Thus, from the first examples alone, it can be concluded that the problematic nature of the entire approach of the central authorities to the implementation of the construction project is even more fundamental, where, as things stood at the time, there were no prospects for addressing the implementation of the BIM mandate in Poland.

On the other hand, from the examples of conducted public procurement proceedings with the provision of the requirement to use BIM for documentation, the first tender of the Museum of Józef Piłsudski project in Sulejówek in Poland is mentioned. Continuing the thought of the problem of the attitude of the parties to the implementation of procurement in the spirit of innovation, the example mentioned was not free of similar problems. From the proceedings, we can detail the failure to adapt the terms of the contract

to the realities of the Polish market, the ignorance of the ordering party and the repeated changes to the content of the announcement, but also the resistance encountered from the main contractors, who cited the lack of the required BIM in Polish law (BIM blog, 2015). Other examples of announced public procurements were tasks in the field of architectural inventory or multi-discipline documentation for construction and detailed design (Orlińska-Dejer, 2017). On the other hand, the literature also popularised public construction projects where BIM was used optionally in the design process (Olszewski, 2014; Olszewski, Gundelach & Jędrychowski, 2014). Despite this, the number of example initiatives to supplement the contract with a record of the use of BIM elements was negligible. Thus, what stands out is the current problem of public sector projects, which is the lack of fundamental knowledge of property developers, and the reluctance of main contractors to implement the contract in BIM. Hence, the issue of addressing the demand for consciously defined standards and the corollary aspect of understanding the actual desirability of receiving the expected final product arises. Undoubtedly, it is desirable to involve the national side in this process and take responsibility for overseeing and leading the BIM implementation process.

One of the central government bodies to which all the mandating of BIM methodology in public procurement comes down is the Public Procurement Office. It is the body that is required to do the most in terms of shaping BIM in the country. As part of the development of the EU directive, a comprehensive 240-page document discussing the modernisation of the regulations was published on behalf of the authority. In the context of the use of digital building data modelling tools, only a provision of the law was rewritten, which was not analysed to any extent (Urząd Zamówień Publicznych [UZP], 2014). Hence, it is necessary to consider this action in terms of wondering how public sector clients could require the use of BIM methodology in the bidding process at all when no uniform field was given to interpret the provision. On the other hand, one must consider the situation of lack of interest in the directive provision due to the absence of any top-down mandated requirement. In turn, there is also the issue of education, which currently is primarily done from the grassroots level.

In contrast, the only education-related activity identified by the central office's initiative was the organisation of a thematic conference in December 2015 on BIM technology in the preparation and implementation of public sector projects. In cooperation with the BIM Association, the Public Procurement Office prepared panels discussing the directive's regulations, the practical use of BIM technology at each stage of a building's life, the BIM Task Group initiative and the openBIM approach in the process. Participants included representatives of the public sector, central and local government entities, and practitioners and experts (Informator Urzędu Zamówień Publicznych, 2015). The conference resulted in the first significant interest in cooperation among smaller municipalities and cities. On the European level, in turn, a task group was funded to harmonise approaches to the use of BIM tools in public procurement across member states. The EU BIM Task Group published, among other things, a handbook with guidelines and a recommendation on key practices, with the accompanying buzzwords being value generation, innovation, and economic growth (EU BIM Task Group, 2016).

After 2014, legislative changes were necessary to adapt the law to EU provisions. The deadline for member states to introduce legislation implementing Directive 2014/24/EU was 18 April 2016. Until then, there was certainly a lack of commitment from the government side and informed decision-makers with whom to work, especially since, given the well-developed parallel grassroots initiative, the opportunities were considerable. The Polish case is, first and foremost, a multi-issue problem. It encompasses many actors with different states of knowledge, and different goals and expectations. The methodology of modelling information about the building can possibly be an answer to these problems, but it seems that the topic of the Polish construction industry has an even more intricate background, which especially requires adequate preparation to adopt a new approach to the implementation of the property development and construction process in the future.

Towards a BIM mandate

The main topic of discussion around the upcoming amendment to the Public Procurement Law was the provision for the use of BIM tools in procurement. The NGO initiative was also present in this regard. An approach negating the obligatory nature of BIM methodology in procurement (*Izba Architektów Rzeczypospolitej Polskiej* – IARP) was present, but there were also observed activities of the BIM Cluster together with the BIM Association, who proposed a revised content of the future law, as did the Polish Association of Construction Engineers and Technicians, and the Association of Polish Architects (Ustinovičius, Wierzowiecki & Puzinas, 2016). On the other hand, despite the efforts, the law was published with an unchanged provision of the European directive, allowing the optional use of digital tools (Article 10e) (Ustawa z dnia 22 czerwca 2016 r. o zmianie ustawy – Prawo zamówień publicznych oraz niektórych innych ustaw). After 2016, one can notice increased initiatives centred strictly around the Ministry of Infrastructure and Construction (in Polish: *Ministerstwo Infrastruktury i Budownictwa* – MIB). At a similar time, there was a parliamentary consultation on the topic of public procurement with a proposal for methods of implementing BIM from the central level. The meeting was held with the participation of specialists from the construction industry, including representatives of universities, the BIM Cluster, the BIM Association, the Association of Polish Architects, IPB, the V4 BIM Task Group, engineers, designers, practitioners working in BIM, as well as legal advisors. Constraints towards national implementation were highlighted, which include procedures incompatible with the assumptions of the methodology, fragmentation of stakeholders, insufficient competence to define requirements in the procurement, and thus, lack of support from specialised advice to public sector clients. In turn, of the actions identified as necessary to be taken, the essence of drawing from foreign experience and adapting existing standards to the specific needs of the Polish market was discussed, as well as the 'indispensable', which is the commitment of the state party to consciously carry out a systemic change in the approach to the implementation of the property development and construction process at the national level. The issue of phasing the implementation process with the introduction of gradual, initially more affordable requirements in public-purpose procurement was emphasised. There were also proposals to draw up templates and contract documents, subsidies, and the appointment of a national coordinator with effective contact with government bodies. The consultations resulted in an interpellation to the MIB (Janota-Bzowski, 2016a; Janota-Bzowski, 2016b). The discussions that were undertaken also mentioned estimating the cost and return on investment for the first implementation of the technology through the development of Malta House in Poznań (Walasek & Barszcz, 2017). Shortly thereafter, on the initiative of the Deputy Minister of MIB, a series of expert meetings on the use of BIM methodology was organised (Builder Polska, 2016). This is the first clearly created opportunity to undertake cooperation between the bottom-up and top-down sides.

At the end of September 2016, a commission was carried out to develop an expert opinion on the possibility of implementing the BIM methodology in Poland, commissioned by the MIB as part of the project '*Wzmocnienie potencjału legislacyjnego w obszarze procesu inwestycyjno-budowlanego* [own translation: Strengthening legislative capacity in the area of the property development and construction process]'. It consisted of an analysis of the current legal regulations regarding the possibility of applying the methodology in public sector projects so that the results would enable the identification of ways to implement BIM in the country from the central level. Foreign practices were presented, among others, on the basis of the British experience, where a special BIM Task Group was established to control the entire implementation process, which was divided into stages; special attention was paid to standardisation of classification; public consultations and meetings were held with stakeholders in the entire process, and pilot projects were implemented involving the Ministry of Justice in the process. The foundation driving subsequent activities to improve national implementation was well-prepared project information. For Poland, on the other hand, KPMG pointed

to a provision in the Public Procurement Law that is at a very general and under-specified level, which can pose a problem in terms of understanding the content and thus make it impossible to require it in procurement proceedings. In addition to this, the scope and method of implementation of the strategy and the necessary basis for the implementation process, which is effective communication with stakeholders, are defined. This implies the need to develop appropriate methods and a plan to lead the dialogue in order to achieve the real involvement of the right people associated with the construction industry (KPMG, 2016).

As a top-down initiative, cooperative consultation activities did not actually continue until 2019. In the middle of the year this time, the Public Procurement Office showed its commitment with a closed workshop meeting on BIM tools in the implementation of infrastructure projects (Urząd Zamówień Publicznych [UZP], 2019a). Further down the line, the same central body organised the BIM Hyde Park, a discussion meeting in proposed thematic blocks (Urząd Zamówień Publicznych [UZP], 2019b). The group of participants again included members of NGOs, representatives of design and contracting companies, and representatives of the public sector. The discussions covered virtually the same topics as the publication of the European Directive five years earlier, namely the issue of regulating the provision of the Public Procurement Law from the use of electronic construction data modelling tools and its interpretation, as well as the financing of a uniform standardisation system and the issue of national involvement in the implementation of pilot projects (Janota-Bzowski, 2019). The circular activities of central institutions can be closed with the publication of a new Public Procurement Law with the rewritten content of the well-known article (Ustawa z dnia 11 września 2019 r. – Prawo zamówień publicznych; Fig. 8).

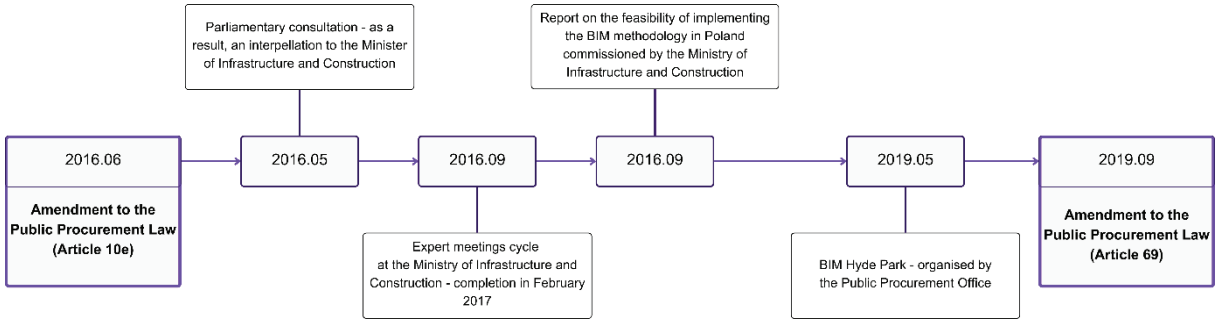


Fig. 8. National steps taken toward a BIM mandate

Source: own work.

Based on the experience of other countries implementing BIM, it was clear that at some point, in the Polish market, it would also be necessary to announce and implement a programme of pilot projects. The identified main projects are shown in the table (Table 1). The selected projects were infrastructure projects. On the other hand, it is well known that BIM technology and tools currently provide better support for cubic buildings, which, in contrast to broadly defined buildings, require the cooperation of a narrower group of specialists from different backgrounds. Thus, the implementation of the aforementioned buildings in BIM technology is not an easy task (Juszczyk, 2022). However, the first pilot was announced for a project selected by the General Directorate of National Roads and Highways (in Polish: *Generalna Dyrekcja Dróg Krajowych i Autostrad* – GDDKiA) (a body under the then Ministry of Infrastructure and Construction), which involved the construction of a slightly more than two-kilometre section of road with the necessary accompanying elements. Preparations involved adapting the procurement requirements to the current state of the Polish market. With the support

of a consultant, participants in the procurement party process were trained, goals to be achieved from the pilot were defined, and a technical dialogue was organised with the main contractors to learn about their readiness to implement the project at the set level. The Employer's/Exchange Information Requirements (EIR) (Karolak et al., 2018) are also included in the tender and contract documents. The mature preparation for the most important project defining the next steps towards the BIM mandate is the only positive element of this construction project. At the time of writing, the final main contractor for the construction of the Zator bypass has still not been selected. On the other hand, further mention can be made of the pilot project for the Polish Railways for the design documentation of the railroad viaduct, which was implemented within two years after the tender was issued.

Table 1. Inventory of the best-known pilot projects since the beginning of the national BIM implementation process

Name of the authority	Project title and scope of work	Year of the first pilot dialogues	Status as of 15 December 2024
General Directorate of National Roads and Highways (*Generalna Dyrekcja Dróg Krajowych i Autostrad* – GDDKiA)	Preparation of project documentation for the task 'Construction of the Zator bypass within the National Road 28'	2016	ongoing (second announcement on contractor selection process)
Polish Railways (*PKP Polskie Linie Kolejowe S.A.*)	Preparation of project documentation for the task 'Demolition and Construction of a Railroad Viaduct at km 33.994 on Railroad Line 140 Katowice Ligota–Nędza'	2016	completed (2020)

Source: own work.

Despite the small number of pilot projects, the Polish construction market has optionally supplemented the provision for the use of BIM methodology in some tendering procedures for public sector projects. Provisions can be found in the technical (geo-referencing, level of detail, file transfer formats such as IFC, specifying the common data environment platform provider, coordination), managerial (how to communicate and share files in a common data environment) and strategic (process control, organisational issues) areas, although this was enforced differently in each case and to a different extent (Zima & Mitera-Kiełbasa, 2021) in addition to the barriers that participants of such projects may face. This paper is a case study of Employer's Information Requirements (EIR). Later, to prevent the differences that may occur at the stage of drafting documents, studies commissioned by the Public Procurement Office as well as the Ministry of Infrastructure were published for contracting authorities and contractors (Ministerstwo Infrastruktury, 2021; Ministerstwo Infrastruktury, 2022; Urząd Zamówień Publicznych, 2022; Kasznia, 2023). However, the mentioned documents are mainly an introduction to carrying out a construction project with BIM, the related terminology, methodology assumptions and basic technical guidelines, which are only a collection of information and guidance. Equally basic recommendations for the contracting authority can be found in the State Procurement Policy of 2022, which also sets out recommendations for the President of the Public Procurement Office to continue educational activities in promoting the use of BIM (Uchwała nr 6 Rady Ministrów z dnia 11 stycznia 2022 r.). The regulation on the scope of data interoperability, which lacks a reference to the IFC standard, is also highly questionable (Rozporządzenie Rady Ministrów z dnia 21 maja 2024 r.).

Attempts to implement the BIM mandate

The preparatory activities for further steps towards the potential implementation of BIM in the country resulted in several significant actions on the part of the central government administration. The essence of this part was primarily to analyse the approach and the general context in which BIM was presented to the audience, as well as the main goal that guided the actions taken by decision-makers. The largest project towards identifying and determining the prospects for future implementation of BIM was the '*Cyfryzacja procesu budowlanego w Polsce* [own translation: Digitisation of the Construction Process in Poland]' project, which was carried out by the former Ministry of Development. The project, which lasted nearly one year, was undoubtedly carried out on the largest scale of activities to date. The study included all participants in the property development and construction process during surveys, meetings, and consultations held to examine and analyse the current state of the construction industry. One of the main objectives was to identify demands for proper preparation and dissemination of best practices carried out by the BIM methodology (Ministerstwo Rozwoju i Technologii [MRiT], 2020a). This was to be helped by workshops with foreign specialists who shared their acquired experience through national implementations. Regular reports and documents were published, presenting the progress of the project work. The resulting studies are mainly aimed at contracting authorities and contractors. An important product is the prepared templates of BIM documents (BIM execution plan or information requirements), along with the discussed standard PN-EN ISO 19650 (Polski Komitet Normalizacyjny [PKN], 2019) in terms of using its elements in the process of construction project implementation. On the other hand, an important highlight is the fact that the documents are strongly based on economic issues. Tomana (2020), in his publication, draws attention to the problem of implementing projects using the macroBIM level. He points out that the documents do not consider the aspect of currently used price lists and what will be difficult at the stage of cost estimation due to their failure to adapt to the requirements of BIM technology. Moreover, they lack a long-term approach, where the most important assumption of the methodology would be included, i.e. the inclusion of the entire life cycle of a building and at least the topic of produced costs (not only financial) during operation. The topics of the project, as much as the actions, would not cover a wide range of stakeholders, but the final conclusions and assumptions are very narrow – to a single, not very clear goal.

Following the example of the UK, a list of elements compiled in a document with the identical name '*Mapa drogowa dla wdrożenia metodyki BIM w zamówieniach publicznych*' [own translation: Roadmap for the Implementation of BIM Methodology in Public Procurement]' was meticulously prepared. A 'strategy matrix' was developed, with components such as technology, cyber security, Lean approach, classification, and ecology. All are considered for each phase of the project process (Ministerstwo Rozwoju i Technologii [MRiT], 2020b). The document presents a timeline with deadlines for achieving the listed components. In addition to this, most interesting is the ambitious milestones set for the presence of BIM in the tender proceedings in question, where, among other things, from 2030 all public procurement would be done using the methodology (Pinkosz & Borkowski, 2023). The document, also called an implementation strategy, is not mandatory. These are merely identified actions to make the audience aware of the importance and essence of BIM and the steps needed for future implementation. The possible updates recommended in the document as to end dates have never happened.

Regardless of the content published earlier, a study 'BIM Standard PL' by NGO authors in cooperation with major contractors and with the participation of the Public Procurement Office (BIM Standard PL, 2020) was also made available in 2020. The publicly available document, intended for cubic buildings, consists of a core part with a glossary of terms and appendices, such as templates or tables for graphic and non-graphic data details. The identified problem with this study is the fact that it is optional and that it is only a proposal

for a standard that can be further improved and introduced with potential national implementation. Further, the theme of the idea of a digital twin, mentioned in the introduction, is not developed virtually at all later on. The vocabulary used is also questionable. Alternatively, one can read about technology, process, and BIM methodology. Despite explanations of these and other terms in the glossary, it is difficult in some cases to find their practical use in the text. The issue of the non-committal nature of the document stands out very strongly. There was no definitive indication of the necessity of creating a Polish classification (Kacprzyk, 2022). There was also a cursory treatment of the file naming standard. By definition, standardisation should be regularly updated, especially because it is an ongoing process. The assumed element of discussion (and the resulting low level of public involvement) with modification and completion of the new version of the manuscript has not been realised so far (Kacprzyk, 2023).

The aftermath of the Digitisation of the Construction Process project was the establishment of the BIM Working Group by the MoD in 2022. The Group existed for more than a year. The Group included people well-known in the BIM community. The activities undertaken can be summarised by the slogan of theoretical enterprise. The reported files mainly include repeatedly identified key issues related to standardisation, classification, standards, preparation of tender documents, support of procurers, and legal changes. The task of the Group was to support the Minister in developing a strategy for the implementation of the methodology (BIM Working Group, 2022). The result of the work worth noting is the '*Koncepcja wdrożenia klasyfikacji budowlanej CCI w Polsce* [own translation: Concept for Implementation of CCI Construction Classification in Poland]'. To achieve consistent data exchange and thus increase productivity, it is argued that CCI classification was chosen because its scheme was developed strictly for BIM. Analysing the Group's work in this regard, one mentions a rather consciously executed study with an indicated constant need for verification, changes and interpretation of the classification. It is, of course, a good effort to refer to the activities of the Polish branch of the buildingSMART Association, which takes care of the maintenance and development of the classification at the international level (Ministerstwo Rozwoju i Technologii [MRiT], 2023). On the other hand, the document was again not binding, and after the breakup of the Group, work on it continued even less.

The current project taking place towards further digitisation of the construction process is the work on the e-Construction web portal, which was launched in 2022. It is a platform for streamlining the work of architectural and construction administration bodies and construction supervision, and the list of construction procedures possible for users has been regulated by law (Ustawa z dnia 7 lipca 1994 r. Prawo budowlane). The assumptions presented on the title site for the digitisation process are divided sequentially into phases of procedures, registers and authorities (e-Budownictwo, n.d.). This is also how other tools are launched over time: a digital construction book (c-KOB) or an electronic construction log (EDB) and others. Currently, the system for administrative procedure support in construction (SOPAB) is being piloted. Ultimately, the system is to be fully integrated with other services, as well as with the General Office of Geodesy and Cartography (in Polish: *Główny Urząd Geodezji i Kartografii* – GUGiK), and the flow of information would take place within the authorities conducting the necessary activities in construction processes (SOPAB, n.d.). The initiative to electrify construction documentation is undoubtedly a necessary process. Nevertheless, the decision to choose the form of submission of applications (for notification, for decision), either in the traditional version or through the portal, is still at the user's discretion. Moreover, when deciding to generate an application on the e-Construction portal, it can still take a paper form to go to the authority as a hard copy, which, in practice, means the continued preference for paper documentation over digital documentation. All attempts at national BIM implementation can be summarised by the statement that none of the initiatives has been officially implemented on the market.

DISCUSSION

The methodology of BIM strongly emanates from and permeates, to a greater or lesser extent, every area of the construction industry's operation. It is now an inherent topic of much discussion and consideration in the approach to the innovative solution, which is permanently entrenched in the minds of many. An undeniable regularity is the fact of the demand for BIM in the drive to digitise the industry. Although it continues to find its opponents and sceptics, the cause of realising certain higher goals should be guided beyond any doubt. In Poland, the benefits of the described methodology are gradually being noticed. An analysis of the current state of national implementation has shown that it is still in the initial stage of implementation work. The identified actions taken over the past years resonated strongly among those involved. Unfortunately, their multitude remained ununified and uncoordinated. The degree of fragmentation of the entire process with stakeholders is considerable.

The adoption of BIM in Poland has been going on for almost twenty years. From the earliest implementations in the Polish branches of foreign companies to waiting for guidelines on standardisation and defining a binding strategy for implementing BIM in public procurement, this period is still growing. During this period, and especially in the first years, the initiative was taken by companies from the AEC industry, which began to adapt the methodology to their own needs. The first implementations took place in large companies with the possibility of investing in new technology and training. I mention technology here because it is where the definition of the new concept that could potentially replace CAD technology and paper documentation begins to take shape in Poland. Inevitably, BIM began to be reduced to the use of new applications and design tools. The accumulation of training offered by software manufacturer partners has turned BIM into a marketing activity rather than an idea introducing a new evolution after the computer-aided design stage. Implementation has led to the development of internal know-how in companies to a greater or lesser extent – sometimes also with a view to reserving it (Borkowski, Nurzyńska, Sender & Wiosna, 2024) – leading to a situation in which companies now admit to using BIM, regardless of whether it is required in the project or not. Ultimately, the benefits of such an implementation will never be maximised, especially when it is at a low level of maturity. The BIM methodology has not been developed solely for individual use; however, BIM now plays an indispensable role in creating new, innovative directions and design ideas. Being competitive in the construction market is an undeniable added value, although one should also consider the issue of some participants in the construction process who, above all, do not notice the wide range of benefits brought by the methodology and, moreover, are convinced of the correctness of many cognitive errors.

Awareness of the possibilities and advantages of BIM implementation increases over time. The very process of popularisation and the stages of development of methodology can be observed in the most frequently cited studies organised periodically by Autodesk. In particular, the different entities show a changing level of BIM awareness over the years, which is also stated in the report (2019 – 38.3%; 2023 – 58.8%) (Autodesk, 2023). This is the average response of those surveyed to the question regarding their contact with BIM methodology in their professional work. The percentages are promising, but as the study shows, practical skills are not enough to fully understand the methodology or to achieve all the benefits it offers. This fact, in turn, was addressed in the subsequent questions of the survey, and there is indeed reason to be optimistic in this respect: the low level of knowledge about BIM (2015 – 60.2%; 2019 – 68.4%; 2023 – 74%) was the main barrier to the implementation of BIM in Poland among respondents (Autodesk, 2019; Autodesk, 2023). Bottom-up activities are effective in shaping the Polish market for the 21st century. This is particularly evident when the use of BIM in individual units is already quite systematised, and in the latest survey, the surveyed process participants (architectural, design, construction companies, developers, managers) also point to the low awareness of the benefits of BIM among developers as another barrier (2023 – 72%) (Autodesk, 2023). A further step towards readiness to enforce the BIM requirement in procurement is evident.

Thus, it is stated that the necessary continuation of educational activities for BIM in the country is needed. The dissemination and sharing of valuable experience should remain a priority in the field of NGO activities. Well-established knowledge and awareness of the assumptions of the BIM methodology among professionals, practitioners and adepts should be strongly emphasised at organised conferences, in published content in trade journals and generally be promoted among the community. The pressure exerted with increasing intensity will result in the presence of BIM in more areas of the industry's operation. As time goes on, there will certainly be an increase in the number of implementations being carried out in design and contracting companies. If the current minimal national interest continues, the disparity between individual use of BIM and its application in public procurement will widen. Companies will develop internal standards for conducting the property development and construction process, which will cause further chaos and possible inaccuracies in interprofessional cooperation and in the implementation of further stages of the project. On the other hand, the competitiveness of Polish companies in the international arena will be increased, and new trends in design, applied solutions on construction sites, and approaches that meet the goals of modern construction will be developed. How independently the bottom-up initiative will still be carried out from the top-down depends solely on the national side.

The prospect of implementing the methodology in public procurement remains at the stage of clumsy attempts to study the needs and opportunities of the construction market. The non-committal nature of the projects, consultations and documents presented have been noted in all the activities undertaken. A standout issue is the continued wait for a decision on the start of a centrally monitored BIM implementation process. The continually maintained optionality of activities will not lead to coordinated implementation. In addition, it is also impossible to achieve measurable results when the electronification of construction documentation remains unmandated. Thus, paper documentation figures will continue to persist: on average, 0.03 M m^3 of storage space is needed annually to store documents for handling construction permits (Rynek Instalacyjny, 2023). Therefore, what is needed is a decision from the government level that will include experienced individuals in the implementation process, and top-down actions will consistently complement bottom-up actions. Toward the mandatory application of BIM in public procurement, activities in the area of standardisation, issuance and dissemination of construction classification in accordance with BIM methodology, along with the development of a good practice manual to support companies implementing BIM, are essential. As in the Czech example, a national knowledge repository (Borkowski, Drozd & Zima, 2024) can also be a basic element. Regularly updated and publicly available handbooks, manuals, and guides can provide the basis for a standardised approach to the implementation of a construction project. In turn, the training of local government units can be carried out along the lines of the training organised by the Ministry of Development and Technology on the future reform of planning and spatial development in Poland (Ministerstwo Rozwoju i Technologii [MRiT], 2024). With the decision to make BIM mandatory in the future, legislative changes should be an integral part. The Polish construction market will not begin to treat the digitisation of the construction process with due respect until there is an amendment to the law making the application of the methodology mandatory in each public contract. The national implementation process should be properly planned and maturely carried out. Real incentives for the use of BIM should be present, properly rewarded in non-price criteria, and subsidised from the governmental and European levels.

A holistic view of the topic of BIM implementation in property development and construction processes has shown that the issue of Polish implementation is very intricate. Significant action is needed in the near term to prioritise the implementation of BIM methodology. A binding decision is needed to start developing a long-term plan supported by the government. It may also be important to take foreign experience into account and realistically set end dates for achieving milestones based

on that experience. An implementation strategy should be drawn up as soon as possible since, apart from the domestic side, there are presently no major oppositions that are hampering the process. A key element should be an independent entity acting for the general good, responsible for overseeing and evaluating the implementation process. In turn, bottom-up action only with top-down action can allow for effective and consistent methodological awareness building.

It is necessary to continue to observe the construction market. As it is one of the least digitised industries in Poland, the constant development of technology and the growing demand for the implementation of advanced construction projects will force adaptation to the requirements of the market. Thus, one can already see attempts to assess individual possibilities of implementing the methodology among procurers, as in the PKP PLK Company launching the BIM Working Group (PKP Polskie Linie Kolejowe S.A., 2024). This shows that interest in BIM is growing, while it is possible that this will lead to the opposite effect, which will be completely different than expected. The demand for BIM is high. Therefore, one of the effects of implementation work in the long term will be to ensure the country's competitiveness on the international stage. In turn, the preparation of future specialists should constantly be based on a uniform curriculum at universities.

CONCLUSIONS

The critical nature of the work has highlighted all the inaccuracies of the existing approach to the topic of mandate implementation in Poland. Building information modelling methodology represents a huge opportunity for the digitisation of the construction industry. Therefore, it is even more desirable to have a responsible body that would guarantee a decision on the coordinated implementation of BIM, starting with public procurement of a specific value. The realised assumptions about the work undertaken were made possible by in-depth literature research. Expanding the analysed content with sources that went beyond formal documents and legal acts made it possible to make a factual assessment of the state of BIM implementation in the country. Thus, inferring the subject matter taken up, the degree of progress on the BIM obligation is minimal. In the current situation, it is even necessary to reorganise the steps towards the mandate. It is necessary to build a fundamental base that assumes the entire life cycle of a building while realising the objectives of European policy and global trends in construction. The approach that assumes only calculations of the potential cost of a product alone should be abandoned. More attention should be paid to the individual – the future user of the construction project, where the greatest tangible and intangible costs of maintaining the building are generated in the operation and management phases. It is advisable to think with much more care about the future, with the prospect of creating digital twins of buildings, and eventually extending to larger areas, such as cities.

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Authors' contributions

Conceptualisation: A.S.B. and G.B.; methodology: A.S.B. and G.B.; validation: A.S.B.; formal analysis: G.B.; resources: G.B.; data curation: G.B.; writing – original draft preparation: A.S.B. and G.B.; writing – review and editing: A.S.B. and G.B.; visualisation: G.B.; supervision: A.S.B.; funding acquisition: A.S.B.

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REFERENCES

Anger, A., Lisowski, B., Piwkowski, W. & Wierzowiecki, P. (2015). Ogólne założenia procesu wdrażania BIM w realizacji zamówień publicznych na roboty budowlane w Polsce. *Przegląd Budowlany*, *10*, 6–9.

Anger, A., Łaguna, P. & Zamara, B. (2021). *BIM dla managerów*. Warszawa: Wydawnictwo Naukowe PWN.

Autodesk. (2019). *BIM, współpraca, chmura w polskim budownictwie – Raport z badania. 2019*. Retrieved from: https://www.zgpzitb.org.pl/wp-content/uploads/2019/11/2Raport_Autodesk_Chmura_A4_14_10_roz.pdf [accessed 11.04.2024].

Autodesk. (2023). *BIM, współpraca, zarządzanie informacją w polskim budownictwie – Raport z badania. 2023*. Retrieved from: https://www.autodesk.com/pl/campaigns/raportbim. [accessed 11.04.2024].

BIM blog. (n.d.). Retrieved from: https://www.bimblog.pl/ [accessed 24.09.2024].

BIM blog. (2015). *Pierwszy w Polsce przetarg publiczny z wymogiem IFC. Część 2*. Retrieved from: https://www.bimblog.pl/2015/01/pierwszy-w-polsce-przetarg-publiczny-z-wymogiem-ifc-czesc-2/ [accessed 4.01.2024].

BIM Standard PL. (2020). Retrieved from: https://www.gov.pl/web/uzp/bim-standard-pl [accessed 9.08.2024].

BIM Working Group. (2022). Retrieved from: https://www.gov.pl/web/rozwoj-technologia/grupa-robocza-do-spraw-bim [accessed 19.12.2024].

BIM4u.eu. (n.d.). Retrieved from: https://bim4u.eu/ [accessed 12.09.2024].

Borkowski, A. S., Drozd, W. & Zima, K. (2024). The Status of the Implementation of the Building Information Modeling Mandate in Poland: A Literature Review. *ISPRS International Journal of Geo-Information*, *13* (10), 343. https://doi.org/10.3390/ijgi13100343

Borkowski, A. S., Nurzyńska, K., Sender, M. & Wiosna, Z. (2024). BIM Placemat – wdrożenie technologiczne produktu w pracy specjalistów BIM w przedsiębiorstwach projektowych Arcadis i WSP Polska. *Builder*, *326*, 2–7. https://doi.org/10.5604/01.3001.0054.7088

Builder Polska. (2016). *Cykl spotkań eksperckich dotyczących metodyki BIM*. Retrieved from: https://builderpolska.pl/2016/09/12/cykl-spotkan-eksperckich-dotyczacych-metodyki-bim/ [accessed 3.12.2024].

Cheng, J. C. P., & Lu, Q. (2015). A review of the efforts and roles of the public sector for BIM adoption worldwide. *Journal of Information Technology in Construction (ITcon)*, *20* (27), 442–478.

Directive 2014/24/EU of the European Parliament and of the Council of 26 February 2014 on public procurement and repealing Directive 2004/18/EC. OJ L 94, 28.3.2014, p. 65–242.

Directive 2014/25/EU of the European Parliament and of the Council of 26 February 2014 on procurement by entities operating in the water, energy, transport and postal services sectors and repealing Directive 2004/17/EC. OJ L 94, 28.3.2014, p. 243–374.

Dorna, S. & Glema, A. (2016). *Procurement and investment procedures and processes in the initial phase of implementation of BIM in Poland*. Paper at the 1st International UK BIM Academic Forum Conference, Glasgow.

e-Budownictwo. (n.d.). Retrieved from: https://e-budownictwo.gunb.gov.pl/ [accessed 19.12.2024].

EU BIM Task Group. (2016). *Podręcznik dotyczący wprowadzenia modelowania informacji o obiektach budowlanych przez europejski sektor publiczny. Działania strategiczne na rzecz efektywności sektora budowlanego: generowania wartości, innowacji i wzrostu gospodarczego*. Retrieved from: www.eubim.eu [accessed 23.01.2024].

Główny Inspektorat Nadzoru Budowlanego, Polski Związek Inżynierów i Techników Budownictwa, Stowarzyszenie Architektów Polskich [GINB, PZIiTB, SAP]. (2023). *Koncepcja wdrożenia klasyfikacji budowlanej CCI w Polsce* (2023). Retrieved from: https://www.gov.pl/attachment/cbf6baa4-d8c0-4caa-a6c3-2e2af8e8b11d [accessed 6.01.2024].

Inspektorat Nadzoru Budowlanego, Polski Związek Inżynierów i Techników Budownictwa & Stowarzyszenie Architektów Polskich [INB, PZIiTB, SARP]. (2014). Porozumienie o współpracy pomiędzy Głównym Inspektorem Nadzoru Budowlanego, Przewodniczącym Polskiego Związku Inżynierów i Techników Budownictwa i Prezesem Stowarzyszenia Architektów Polskich. Retrieved from: https://www.sarp.pl/pliki/1940_545b62a807878-porozumienie_gunb-pzitb-sarp.pdf [accessed 12.09.2024].

Janota-Bzowski, J. (2016a). Propozycje dotyczące wdrożenia BIM w Polsce. *Materiały Budowlane*, *7*, 106.

Janota-Bzowski, J. (2016b). BIM – konsultacje sejmowe. *Rynek Instalacyjny*, *7–8*, 22.

Janota-Bzowski, J. (2019). BIM-Hyde Park w UZP. *Rynek Instalacyjny*, *7–8*, 13.

Juszczyk, A. (2022). BIM in the construction process – selected problems at the stage of implementation in Polish road engineering. *Archives of Civil Engineering*, *68* (1), 623–633. https://doi.org/10.24425/ace.2022.140190

Kacprzyk, Z. (2022). *Projektowanie w procesie BIM*. Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej.

Kacprzyk, Z. (2023). BIM Standard PL. *Budownictwo i Prawo*, *26* (3), 22–24.

Karolak, M., Kasznia, D., Bohatkiewicz, J., Dudek, P., Gaweł, M., Magiera, J., Owerko, T., Rajchel, R., Salamak, M. & Wierzowiecki, P. (2018). Projekt pilotażowy zastosowania technologii BIM w GDDKiA przy projektowaniu i budowie obwodnicy Zatoru. *Magazyn Autostrady*, *10*, 83–89.

Kasznia, D. (2023). *BIM dla sektora publicznego – zagadnienia związane z wymaganiami informacyjnymi zamawiającego*. Warszawa: Urząd Zamówień Publicznych.

Kasznia, D. Magiera, J. & Wierzowiecki, P. (2018). *BIM w praktyce Standardy Wdrożenie Case Study*. Warszawa: Wydawnictwo Naukowe PWN.

KPMG. (2016). *Building Information Modeling – Ekspertyza dotycząca możliwości wdrożenia metodyki BIM w Polsce*. Warszawa.

Magiera, J., Czaplejewicz, A. & Wala, K. (2021). Słownik podstawowych pojęć i terminów norm ISO 19650-1 i 19650-2 – Propozycja polskiej terminologii BIM. *Builder*, *25* (5), 68–77. https://doi.org/10.5604/01.3001.0014.8428

Mazovian OIIB. (n.d.). *Możliwości kształcenia podyplomowego w zakresie metodologii BIM*. Retrieved from: https://maz.piib.org.pl/komisja-ds-bim/20-komisje-i-zespoly/komisje-i-zespoly-informacje/1394-mozliwosci-ksztalcenia-podyplomowego-w-zakresie-metodologii-bim [accessed 23.09.2024].

Miecznikowski, P. (2013). BIM – wybór czy konieczność? *Materiały Budowlane*, *10*, 59.

Miecznikowski, P. (2014a). Perspektywy wdrażania BIM na polskim rynku w 2014 roku. *Materiały Budowlane*, *1*, 58–59.

Miecznikowski, P. (2014b). BIM – wyzwania w obszarze Prawa budowlanego oraz Ustawy o zamówieniach publicznych. *Materiały Budowlane*, *3*, 64–65.

Miecznikowski, P. (2014c). Możliwość wykorzystania BIM w zamówieniach publicznych w Polsce. *Materiały Budowlane*, *4*, 70.

Miecznikowski, P. (2014d). Czy generalny wykonawca robót budowlanych potrzebuje BIM? *Materiały Budowlane*, *8*, 52−53.

Ministerstwo Infrastruktury [MI]. (2021). *BIM-M-01 Powiązanie wymagań technicznych dotyczących drogowych obiektów inżynierskich z technologią BIM*. Retrieved from: https://www.gov.pl/attachment/3ce9ead6-08d8-4e11-80a8-5d22124eddff [accessed 6.01.2024].

Ministerstwo Infrastruktury [MI]. (2022). *BIM-D-01 Wprowadzenie do stosowania technologii BIM w budownictwie drogowym*. Retrieved from: https://www.gov.pl/attachment/98164b3b-53be-4e2b-91f2-6f6983ebe443 [accessed 12.12.2024].

Ministerstwo Rozwoju i Technologii [MRiT]. (2020a). *Cyfryzacja procesu budowlanego w Polsce – zakończenie projektu*. Retrieved from: https://www.gov.pl/web/rozwoj-technologia/cyfryzacja-procesu-budowlanego-w-polsce--zakonczenie-projektu [accessed 16.12.2024].

Ministerstwo Rozwoju i Technologii [MRiT]. (2020b). *Mapa drogowa dla wdrożenia metodyki BIM w zamówieniach publicznych*. Retrieved from: https://www.gov.pl/web/rozwoj-technologia/mapa-drogowa-dla-wdrozenia-metodyki-bim-w-zamowieniach-publicznych [accessed 23.11.2024].

Ministerstwo Rozwoju i Technologii [MRiT]. (2024). *Reforma planistyczna – cykl konferencji szkoleniowych z wysoką frekwencją*. Retrieved from: https://www.gov.pl/web/rozwoj-technologia/reforma-planistyczna--cykl-konferencji-szkoleniowych-z-wysoka-frekwencja [accessed 3.01.2025].

Mitera-Kiełbasa, E. & Zima, K. (2024a). BIM Policy in Eastern Europe. *Civil and Environmental Engineering Reports*, *33* (4), 14–22. https://doi.org/10.59440/ceer/177606

Mitera-Kiełbasa, E. & Zima, K. (2024b). BIM Policy Trends in Europe: Insights from a Multi-Stage Analysis. *Applied Sciences*, *14* (11), 4363. https://doi.org/10.3390/app14114363

Olszewski, T. (2013). Oprogramowanie wykorzystywane w procesie Modelowania Informacji o Budynku (BIM). *Materiały Budowlane*, *9*, 66–68.

Olszewski, T. (2014). BIM w praktyce: projekt świetlika B Dworca Łódź Fabryczna. *Materiały Budowlane*, *11*, 218–219.

Olszewski, T., Gundelach, J. & Jędrychowski, W. J. (2014). Wykorzystanie BIM przy projekcie Centrum Kongresowego ICE w Krakowie. *Materiały Budowlane*, *5*, 122.

Orlińska-Dejer, K. (2017). BIM w przetargach publicznych – Analiza wybranych postępowań przetargowych. *Materiały Budowlane*, *1* (10), 139–141. https://doi.org/10.15199/33.2017.10.43

Pinkosz, M. & Borkowski, A. S. (2023). Problematyka implementacji BIM na poziomie krajowym. *Przegląd Budowlany*, *94*, 116–121. https://doi.org/10.5604/01.3001.0053.6994

Piwkowski, W. (2017). *Edukacja BIM*. Retrieved from: https://damassets.autodesk.net/content/dam/autodesk/www/campaigns/emea/docs/bim-day-standardy-i-legislacja-polska-i-europa-edukacja-wiktor-piwkowski.pdf [accessed 12.09.2024].

PKP Polskie Linie Kolejowe S.A. (2024, 12 June). *Wznowienie prac Forum Inwestycyjnego PLK S.A*. Retrieved from: https://www.plk-sa.pl/o-spolce/biuro-prasowe/informacje-prasowe/szczegoly/wznowienie-prac-forum-inwestycyjnego-plk-sa-9805 [accessed 13.12.2024].

Polska Izba Inżynierów Budownictwa [PIIB]. (2019). *Strategia Polskiej Izby Inżynierów Budownictwa w zakresie wdrażania BIM, miejsca i roli Izby w tym procesie oraz wskazania sposobów realizacji tej strategii*. Retrieved from: https://www.piib.org.pl/pliki/organy/krajowa-rada/ukr/uchwaly-krajowej-rady-piib-2020-r/Strategia-ds-BIM-02.03.2020.pdf [accessed 12.09.2024].

Polski Komitet Normalizacyjny [PKN]. (2019). *Organizacja i digitalizacja informacji o budynkach i budowlach, w tym modelowanie informacji o budynku (BIM). Zarządzanie informacjami za pomocą modelowania informacji o budynku* (PN-EN ISO 19650).

Rozporządzenie Rady Ministrów z dnia 21 maja 2024 r. w sprawie Krajowych Ram Interoperacyjności, minimalnych wymagań dla rejestrów publicznych i wymiany informacji w postaci elektronicznej oraz minimalnych wymagań dla systemów teleinformatycznych. Dz.U. 2024 poz. 773 [Regulation of the Council of Ministers of 21 May 2024 on the National Interoperability Framework, minimum requirements for public registers and the electronic exchange of information, and minimum requirements for telecommunication systems. Journal of Laws 2024 item 773].

Rydzy, A. (2021). Współpraca Komisji ds. BIM Krajowej Rady PIIB i buildingSMART Polska. *Inżynier Budownictwa*, *9*, 12–13.

Rynek Instalacyjny. (n.d.). *Trwa pilotaż systemu do obsługi postępowań administracyjnych w budownictwie*. Retrieved from: https://www.rynekinstalacyjny.pl/artykul/aktualnosci/162322,trwa-pilotaz-systemu-do-obslugi-postepowan-administracyjnych-w-budownictwie [accessed 30.12.2024].

Salamak, M. (2021). *BIM w cyklu życia mostów*. Warszawa: Wydawnictwo Naukowe PWN.

SOPAB. (n.d.). Retrieved from: https://sopab-pilotaz.gunb.gov.pl/ [accessed 19.12.2024].

Tomana, A. (2016). *BIM innowacyjna technologia w budownictwie: Podstawy, standardy, narzędzia*. Kraków: PWB Media Zdziebłowski.

Tomana, A. (2020). BIM – nowe opracowania. *Materiały Budowlane*, *10*, 59–60.

Uchwała nr 6 Rady Ministrów z dnia 11 stycznia 2022 r. w sprawie przyjęcia Polityki zakupowej państwa. MP 2022 poz. 125 [Resolution No. 6 of the Council of Ministers of 11 January 2022 on the adoption of the State Procurement Policy. Official Journal of the Republic of Poland 2022 item 125].

Urząd Zamówień Publicznych [UZP]. (2014). *Zamówienia publiczne w Unii Europejskiej po modernizacji – nowe unijne dyrektywy koordynujące procedury udzielania zamówień publicznych*. Retrieved from: https://www.uzp.gov.pl/__data/assets/pdf_file/0030/24879/UZP_dyrektywy.pdf [accessed 4.01.2024].

Urząd Zamówień Publicznych [UZP]. (2015). *Informator Urzędu Zamówień Publicznych*, *4*, 14–15.

Urząd Zamówień Publicznych [UZP]. (2019a). *Spotkanie warsztatowe dot. narzędzi typu BIM*. Retrieved from: https://www.gov.pl/web/uzp/spotkanie-warsztatowe-dot-narzedzi-typu-bim---20190514 [accessed 23.11.2024].

Urząd Zamówień Publicznych [UZP]. (2019b). *BIM–Hyde Park spotkanie dyskusyjne*. Retrieved from: https://www.gov.pl/web/uzp/bimhyde-park-spotkanie-dyskusyjne---20190527 [accessed 4.01.2024].

Urząd Zamówień Publicznych [UZP]. (2022). *BIM – innowacyjne podejście do zamówień publicznych w sektorze budowlanym*. Warszawa–Gdańsk: Urząd Zamówień Publicznych.

Ustawa z dnia 7 lipca 1994 r. Prawo budowlane. Dz.U. 2024 poz. 725 [Act of 7 July 1994 – Construction Law. Journal of Laws 2024 item 725].

Ustawa z dnia 22 czerwca 2016 r. o zmianie ustawy – Prawo zamówień publicznych oraz niektórych innych ustaw. Dz.U. 2016 poz. 1020 [Act of 22 June 2016 amending the Public Procurement Law and certain other acts. Journal of Laws 2016 item 1020].

Ustawa z dnia 11 września 2019 r. – Prawo zamówień publicznych. Dz.U. 2019 poz. 2019 [Act of 11 September 2019 – Public Procurement Law. Journal of Laws 2019 item 2019].

Ustinovičius, L., Wierzowiecki, P. & Puzinas, A. (2016). Modelowanie informacyjne budowli (BIM) – stan rozwoju i perspektywy wdrażania w Polsce. *Innowacje w Zarządzaniu i Inżynierii Produkcji*, *1*, 899–900.

Walasek, D. & Barszcz, A. (2017). Analysis of the Adoption Rate of Building Information Modeling [BIM] and its Return on Investment [ROI]. *Procedia Engineering*, *172*, 1227–1234. https://doi.org/10.1016/j.proeng.2017.02.144

Zima, K. & Leśniak, A. (2013). Limitations of Cost Estimation Using Building Information Modeling in Poland. *Journal of Civil Engineering and Architecture*, *7* (5). https://doi.org/10.17265/1934-7359/2013.05.004

Zima, K. & Mitera-Kiełbasa, E. (2021). Employer's Information Requirements: A Case Study Implementation of BIM on the Example of Selected Construction Projects in Poland. *Applied Sciences*, *11* (22), 10587. https://doi.org/10.3390/app112210587

Zintegrowany Rejestr Kwalifikacji [ZRK]. (n.d.). *Kwalifikacje dostępne w Zintegrowanym Rejestrze Kwalifikacji (ZRK)*. Retrieved from: https://kwalifikacje.gov.pl/k [accessed 1.03.2025].

PRZEGLĄD KRYTYCZNY WDROŻENIA MODELOWANIA INFORMACJI O BUDYNKU (BIM) W PROCESACH INWESTYCYJNYCH W POLSCE: DOGŁĘBNE SPOSTRZEŻENIA

STRESZCZENIE

Postępująca cyfryzacja branży budowlanej powoduje globalne zainteresowanie metodyką modelowania informacji o budynku (BIM). Wiele krajów z racji, że dostrzegło niesione przez nią wymierne korzyści, zdecydowało się na rozpoczęcie prac nad implementacją tzw. mandatu. Oznacza to określenie krajowych planów wdrożenia oraz wprowadzenie regulacji prawnych. Celem artykułu było głębokie studium i kwerenda literatury dotycząca aktualnego stanu wdrożenia BIM w Polsce. W ramach usystematyzowanej realizacji pracy zbadano dotychczasowe działania centralnych organów administracji rządowej w kierunku tzw. mandatu BIM. Wykazano chronicznie podtrzymywaną fakultatywność stosowania BIM w zamówieniach publicznych, a także brak skoordynowanych działań odgórnych, jako że odgrywają one główną rolę na drodze krajowej implementacji. Ponadto przedstawiono istotę działalności organizacji pozarządowych w procesie popularyzacji BIM. Wynikiem analizy krytycznej były oceny oraz dyskusja możliwych przyszłych kierunków wdrażania BIM w Polsce.

Słowa kluczowe: modelowanie informacji o budynku, mandat BIM, wdrożenie, implementacja, proces inwestycyjny

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PERFORMANCE OF AGRO-WASTE SUGARCANE BAGASSE ASH IN CONCRETE UNDER DURABILITY TESTS

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ABSTRACT

The concrete industry frequently uses waste material known as sugarcane bagasse ash (SCBA) because of its excellent pozzolanic qualities. Cement is a rare and essential component of concrete construction that is in high demand all over the world. Meanwhile, carbon dioxide (CO_2) is generated widely due to the infrastructure development in the construction sector. To lower CO_2 emissions, concrete must contain less cement. Replacing some of the cement in concrete with agricultural wastes such as rice husks and sugar cane bagasse significantly reduces the material's environmental impact. Therefore, this study focuses on the durability performance of concrete with sugarcane bagasse ash as a partial replacement for cement at 5%, 10% and 15% by weight. The durability of the concrete was studied through the electrical resistivity test, rapid chloride infiltration test, initial surface absorption test, as well as carbonation after 7 days and 28 days. It was observed that the SCBA is a pozzolanic substance with good binder qualities that may be utilised in concrete mixtures to partially replace costly cement.

Keywords: agro-waste, sugarcane bagasse ash, durability, concrete

INTRODUCTION

The most popular construction material is concrete. The demand for ordinary portland cement (OPC) is rising at an alarming rate, with its production predicted to increase by over 50% between 2017 and the end of 2050. For every tonne of OPC produced, an estimated 1 tonne of carbon dioxide (CO_2) will be released (Mohammadinia et al., 2018). Various research studies have investigated the possibility of using processed or unprocessed ash as a cement replacement material (CRM), while there is an abundance of agro-industrial, agricultural and industrial by-products. Fly ash, silica fume, and ground granulated blast furnace slag (GGBS) are well-known CRMs that have shown potential in high-performance concrete. India is the world's second-largest producer of bagasse ash from sugarcane (SCBA) after Brazil. Typically, alternate products for building materials in the construction industries are made from industrial and agricultural waste. The primary goal of employing these components in concrete is to avoid damaging the environment when these waste products are disposed of. Global sugarcane production is nearly 1,500 million tonnes, whereas India produces 8.8 million tonnes of SCBA and almost 670 million tonnes of bagasse ash as a by-product. Worldwide sugar production is explained in Figure 1. By recycling the waste from the industrial and agricultural sectors, researchers are working to create infrastructure and protect the environment

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from the dangerous contamination of silica, various oxides, and unburned particles (Joshaghani & Moeini, 2017). According to Rahimah, Nasir and Kusbiantoro (2015), ash burned at extremely high temperatures will not exhibit high reactivity. According to Cordeiro, Andreão and Tavares (2019), SCBA's crystalline characteristics were changed to an amorphous state by calcining it at 600°C. This enhances the pozzolanic property of the ash.

Reducing the adverse environmental effects and, consequently, pollution is the primary goal of using industrial and agricultural waste in concrete, and SCBA is one of the primary agriculture by-products that has mineral applications. Producing cement involves profound environmental effects as it produces a significant amount of carbon emissions along with other compounds. According to current research, using SCBA instead of cement increases the pozzolanic property and produces good results for compressive strength (Jha Sachan & Singh, 2021).

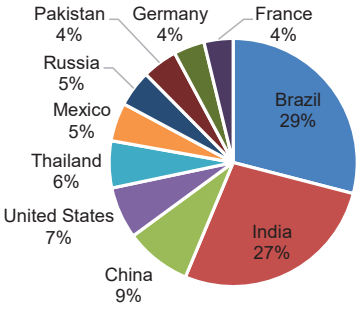


Fig. 1. Worldwide production of sugar in 2024

Source: own work.

A larger number of and different cement (cementitious) materials have been used recently in an effort to lower the amount of cement used and, thus, CO_2 emissions. Meanwhile, there is a huge amount of agricultural waste (AW), which is often in the form of ash following its use in generating energy, as a result of the significant increase in demand for agricultural products. Ashes from agricultural waste were combined with clay and lime, then mixed for two days to create a strongly linked cement-like substance (Heniegal, Ramadan, Naguib & Agwa, 2020). Ash from various agricultural wastes has lately been shown by researchers to be a feasible material for use in the concrete industry. Due to their high concentrations of CaO, SiO_2, Al_2O_3, and Fe_2O_3, agricultural wastes can partially replace conventional stabilisers like cement and quicklime. Green concrete, which is more sustainable and kinder to the environment, can be produced in the concrete industry by using agricultural residual ash (Zeyad, Johari, Tayeh & Yusufet, 2016; Amin, Tayeh & Agwaet, 2020). For pozzolan materials, the most often used specification is ASTM C618-22 (ASTM International [ASTM], 2022). The total oxide concentrations in the chemical compounds SiO_2, Al_2O_3, and Fe_2O_3 must be greater than 70% in order for a material to be considered pozzolanic and have CO_2 and CaO contents (Thomas et al., 2021). From previous studies, it was concluded that bagasse ash – by-product of sugarcane processing – contains high amounts of silica (SiO_2) and alumina (Al_2O_3), which is similar to cement. It was also confirmed that once bagasse ash is finely ground, it can meet the pozzolanic activity requirements as per ASTM C618-22 and, as per previous research, has comparable or even superior strength to conventional concrete. This has been observed when the replacement amount is 5–20%. Bagasse ash reduces water absorption and increases its resistance to sulphate chloride attacks, while also reducing the concrete's porosity.

MATERIAL AND METHODS

The following materials were utilised to make the concrete mixes in the lab. According to Indian standard recommendations, OPC of grade 43 is used along with sand, gravel, superplasticiser, water and SCBA as a partial replacement of the cement by weight.

Cement. In this experimental study, grade 43 OPC was used, meeting the IS 269:2015 specifications (Bureau of Indian Standards [BIS], 2015) and possessing a specific gravity of 3.15. A residue of 8.5% remained on the 90 µm IS-sieve (Indian Standard sieve) and 33% was the usual consistency of the selected OPC. The cement's physical characteristics after conducting the necessary tests were as follows.

Fine aggregate. According to IS 383:2016 (BIS, 2016), Zone II river sand with particle sizes smaller than 4.75 mm but larger than 600 µm was utilised as a fine aggregate in this investigation. The specific gravity of the sand is 2.51, its fineness modulus is 2.65, and its water absorption rate is 1.3%. The bulk density of the fine aggregates was found to be 1,545 $kg \cdot m^{-3}$. The sand was found to be free of silt, clay, and biological contaminants.

Gravel. Natural gravel that was crushed into 4.75 mm and 20 mm sizes and was in compliance with IS 383:2016 specifications was utilised as the coarse aggregate. Its 2.69 specific gravity was determined to be acceptable. The water absorption was 0.7%, and the fineness modulus was 7.1. This large aggregate has a bulk density of 1,610 $kg \cdot m^{-3}$.

Water. Concrete mixing water should not contain any unwanted organic materials or excessive amounts of inorganic components. Concrete can also be made from water that satisfies specified requirements, such as being devoid of organic waste and having a pH of 6–8. Sodium and potassium carbonates and bicarbonates influence the setting time of cement. The specimen was cast and cured using tap water that conformed to IS 456:2000 specifications (BIS, 2000).

Sugarcane bagasse ash (SCBA). After the juice is extracted from sugar cane, the remaining fibrous agricultural waste is called bagasse. First, sugarcane was washed under running water to eliminate impurities like sand that can alter the reactivity of the ash. The SCBA possesses pozzolanic qualities. After burning dry bagasse at 500°C, bagasse ash is produced. Its particular surface area, absorbance, surface response, etc., are improved after burning. It is classified as solid waste and is frequently dumped in landfills. The silica content present in SCBA is around 62%, along with small amounts of Al_2O_3, CaO, Fe_2O_3, and K_2O. A 10% loss of ignition (LOI) suggests a significant concentration of organic materials that has not been burned. Quartz and cristobalite are the two main crystalline phases that can be found in sugarcane bagasse ash (SiO_2). The SCBA utilised in this study was transported from a nearby sugar plant in Kapurthala, Punjab. Following sufficient grinding, the SCBA's specific surface area was 2,550 $m^2 \cdot kg^{-1}$, its bulk density was 580 $kg \cdot m^{-3}$, and its specific gravity was 2.4.

Superplasticiser. Superplasticisers assist in enhancing the early flowability properties of concrete and enable water content reductions of up to 30% without affecting the workability. A poly naphthalene sulphonate superplasticiser was utilised in this investigation at a dosage of 1% of the cement's weight, having a specific gravity of 1.1.

RESULTS AND DISCUSSION

Four different M40-grade mixes were prepared in accordance with IS 10262:2019 specifications (BIS, 2019). Specimens in the form of 100 × 100 m cylinders and 150 mm cubes were cast using these mixes (Table 1) and kept in curing tanks for up to 28 days.

Table 1. Mix design

Name	Type of mix	w/c	Cement [kg]	SCBA [kg]	Water [l]	Gravel [kg]	Sand [kg]	Superplasticiser [ml]
Mix 1	100% OPC	0.36	412	–	148	1,257	666	4.12
Mix 2	5% SCBA + 95% OPC	0.36	391.4	20.6	148	1,257	666	4.12
Mix 3	10% SCBA + 90% OPC	0.36	370.8	41.2	148	1,257	666	4.12
Mix 4	15% SCBA + 85% OPC	0.36	350.2	61.8	148	1,257	666	4.12

OPC – ordinary portland cement, SCBA – sugarcane bagasse ash.

Source: own work.

Mechanical tests on concrete

Compressive strength testing is the most popular since it directly relates to the strength of the structure. All the samples created for the strength tests are 150 × 150 × 150 mm cubes that were cast using various mixtures. The mixture information is shown in Table 1. The samples were demoulded and placed in a curing tank after 24 h, then at 7 days and 28 days, cubes of curing material were extracted for testing in a compression testing machine. It was found that all the blended mixes (Mixes 2–4) had good strengths comparable to the base mix (Mix 1). To properly evaluate how SCBA affects concrete's qualities and draw conclusions on how these mineral-based additives affect concrete's durability, the specimens were tested using a variety of standard testing methods at intervals of up to 28 days.

Compressive strength of blended concrete

In order to examine the behaviour of the three blended concretes and one conventional concrete, 150-millimetre cubes were cast for each of the four mixes. Following the casting process, the specimens were demoulded and allowed to cure in potable water for a day. After the 7 days and 28 days that are advised for curing, the cubes were removed from the water and allowed to air dry before being exposed to high temperatures. At 7 days and 28 days, the 150-millimetre sample cubes were subjected to compressive strength testing for every age and percentage cement replacement configuration. Only Mix 3 exhibited better compressive strength after 7 days and 28 days (Fig. 2) compared to the other mixes, according to the compressive strength test findings.

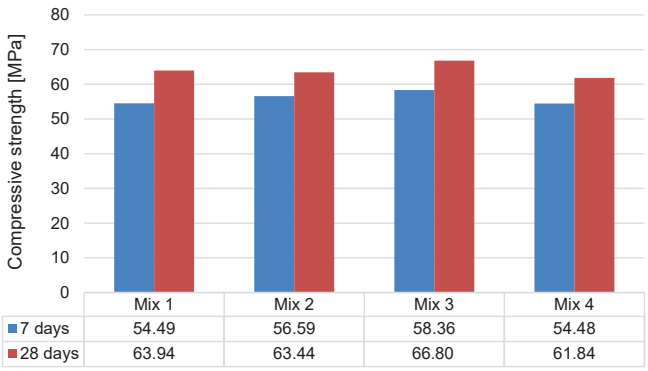


Fig. 2. Compressive strength test results after 7- and 28-day curing periods for all blended concrete samples

Source: own work.

Compared to normal concrete after 28 days of curing, it was determined that the influence of SCBA at a 10% cement replacement was considerable. The significant increase in compressive strength may be due to improved particle packing and the formation of strong hydration products. It was also observed that increasing the percentage of bagasse ash reduced the compressive strength of the concrete after 7 days and 28 days of curing.

Tensile strength test results of blended concrete

Tensile strength is the concrete's capability to withstand an amount of force or resist a tensile force applied to a concrete sample without breaking. The split tensile strength percentages after 7 days and 28 days of curing are shown in Figure 3. Mix 3 exhibited a higher tensile strength value than the other three blended concretes. The increase in strength after 28 days of curing was due to a better stress distribution and increased tensile strength resulting from the fine bagasse ash particles filling in the concrete's voids, increasing its density, and decreasing microcracks. It was observed that there was an approximately 30–35% increment in tensile strength after 7 days of curing.

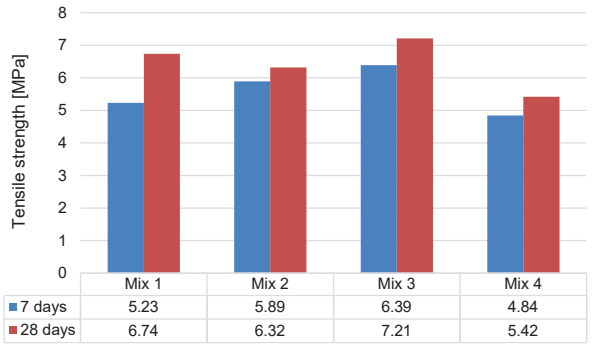


Fig. 3. Split tensile strength result after 7- and 28-day curing periods for all blended concrete samples

Source: own work.

Durability tests on blended concrete

Electrical resistivity test

To evaluate the concrete's resistance to corrosion, the AASTHO TP 95 (American Association of State Highway and Transportation Officials [AASHO], 2011) and ASTM C 1202-10 (ASTM, 2010) standards governed this test, known as the initial surface absorption test (ISAT). One of the non-destructive techniques for assessing the durability and quality of concrete is the electrical resistivity test. This test is beneficial in determining the uniformity, permeability, and probability of reinforcing corrosion. A four-probe apparatus is placed on a damp surface during the procedure. The two exterior probes are placed along the sample, allowing current to flow through the sample while the inside probes maintain the required potential difference. The electrical resistivity test examines how well the concrete can tolerate corrosive solutions passing through it since it depends on the pace at which ions travel. The corrosion risk is assessed using the threshold values listed in ASTM C 1202-10. Higher moisture and ion contents are indicated by a low resistivity value, which could accelerate the corrosion of embedded steel reinforcement. In this research, as per the ASTM standard, our resistivity value lied between 20 $k\Omega \cdot cm^{-1}$ and 50 $k\Omega \cdot cm^{-1}$, which means it has very little possibility of corrosion. Electrical resistivity readings were obtained 7 days and 28 days after curing. When compared to the base mixture, the resistivities

of all three blended mixes significantly improved. The resistivity at 28 days was 6% higher for 10% SCBA-blended concrete than for 15% SCBA-blended concrete, with their similar values being 69.2% and 79.5%, respectively, whereas 5% SCBA displayed an observed value of 72.4% (Fig. 4).

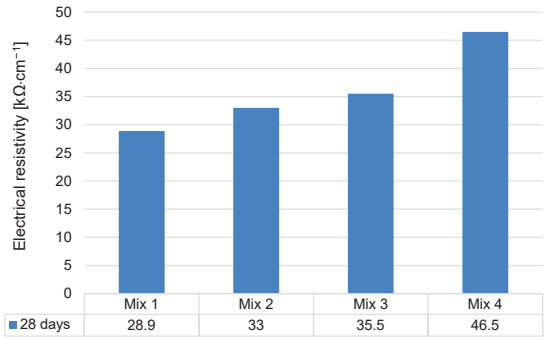


Fig. 4. Electrical resistivity results after 28-day curing period for all blended concrete samples

Source: own work.

Rapid chloride penetration test

A primary cause of corrosion in reinforced concrete is the penetration of chloride ions. To determine how resistant concrete is to chloride ion infiltration, the rapid chloride infiltration test (RCPT) is utilised. This is a popular technique for evaluating concrete's resistance to the infiltration of chloride ions. It offers an indirect measure of concrete's durability, particularly in situations where corrosion of steel reinforcing from chloride is a problem (e.g., sea constructions, bridges). The ASTM C 1202-10 guidelines were adhered to in this work. A 50-millimetre-thick cylindrical concrete disc was submerged for six hours in a 3% NaCl solution and a NaOH solution with two cells with 0.3N 60 V flowing through it (Fig. 5). Analysis of the 28-day data revealed that the RCPT values of the SCBA 10% mix were remarkably high, as seen in Figure 5, while the RCPT values of the SCBA 5% and 15% mixes were lower. This could be due to the SCBA particles, which drastically changed the concrete's pore structure. As per the ASTM C 1202-10 standard, the RCPT value shows that it has very low concrete chloride permeability; the RCPT value decreased due to pozzolanic reactions in the blended concrete with a higher SCBA percentage. The same trend is observed by Ramasamy (2012).

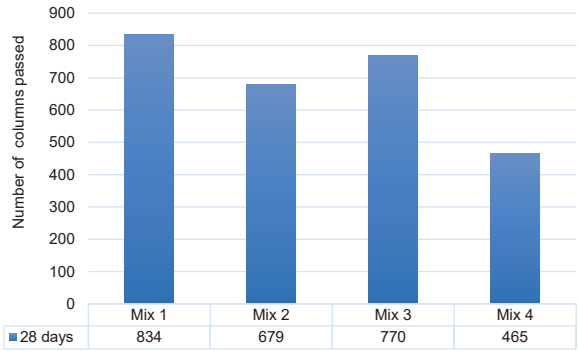


Fig. 5. Test results after 28 days of chloride penetration for all blended concrete samples

Source: own work.

Initial surface absorption test (ISAT)

The initial surface absorption test (ISAT) was conducted following the BS 1881-208:1996 standard (BSI, 1996). To determine the concrete's ability to absorb surface water, the rate of water penetration per unit area of concrete can be determined using a constant water head of 18–20 cm (Fig. 6). The penetrability characteristics of the surface zone have a major influence on concrete's performance in difficult conditions. There is a significant reduction in the corrosion of reinforced concrete members if the concrete covering is less permeable to strong fluids.

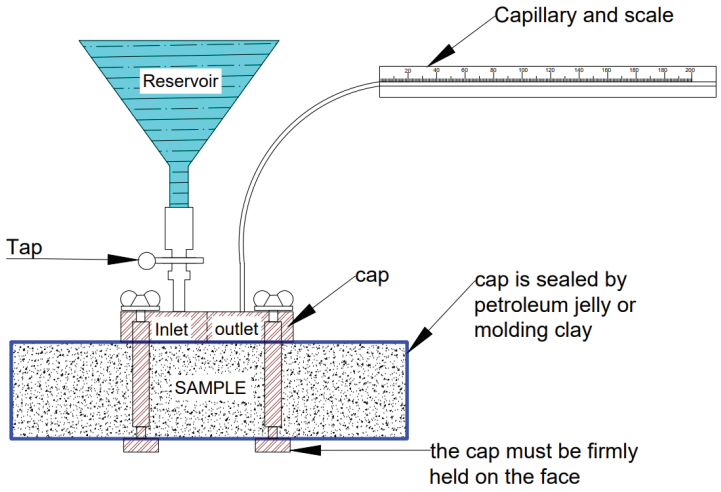


Fig. 6. Setup for initial surface absorption test

Source: Balakrishna, Mohamad, Evans and Rahmanown (2018).

At 28 days, the 10-minute ISAT values of SCBA mixed concrete exhibited a 54.8% improvement, as shown in Figure 7. It becomes more difficult to transport fluid in blended mixes because the pozzolanic processes tend to refine the capillary pore system. Similar patterns were observed by Chi (2012) and Olufemi (2017).

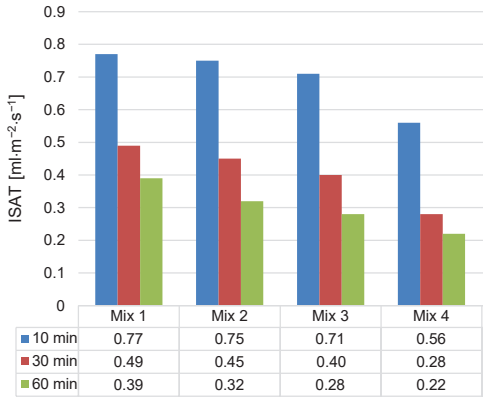


Fig. 7. Initial surface absorption test results after 28 days of curing for all blended concrete samples

Source: own work.

Carbonation test

This is one method for determining how deeply carbonation has occurred in concrete. In concrete, carbonation occurs when the calcium hydroxide [$Ca(OH)_2$] and atmospheric CO_2 mix to form calcium carbonate ($CaCO_3$). The pH of the concrete is lowered by this procedure, which may cause the embedded steel reinforcement to corrode. Table 2 shows the measured carbonation depths for the different mixes. The $Ca(OH)_2$ in concrete has a tendency to maintain a pH of 12.5–13.5, reducing corrosion. An acidic environment is produced while the carbonation process continues, which significantly raises the risk of corrosion.

Table 2. Carbonation depth

Mix	Carbonation depth [mm]	
	after 7 days	after 28 days
1	0	0
2	0	0
3	0	0
4	0	2

Source: own work.

To evaluate the carbonation of the samples, five sides of 100-millimetre concrete cubes coated with epoxy paint and exposed to CO_2 were used (Figs 8 and 9). The samples were placed in a carbonation chamber with a CO_2 concentration of 4–5% and a relative humidity of 55–65%. after removing them from carbonation chamber, the samples are cut in half and phenolphthalein is sprayed on the sample. The depth of the carbonation was measured at predetermined intervals. It was discovered that the 2 mm carbonation depth in Mix 4 with 15% SCBA was equal to up to 28 days of CO_2 exposure, as shown in Table 2.



Fig. 8. Specimens coated with epoxy

Source: own work.



Fig. 9. Phenolphthalein sprayed on samples

Source: own work.

CONCLUSIONS

The mechanical and durability test results are satisfactory, indicating that SCBA can be used to replace fine aggregate in concrete. One of the best substitutes for fine aggregate is found to be SCBA. It is also one of the workable options for making use of leftover ash, as opposed to disposing of it to landfill. The SCBA must be correctly calibrated at 600°C for two days in order to achieve all these optimal results,

which makes it stronger and more resilient than regular concrete. This change also has no detrimental effects on the environment.

The findings make it reasonable to draw the following conclusions:

– Without changing the water-to-cement ratio, the ideal proportion of SCBA (10% replacement of cement) significantly increases the workability of concrete compared to the control mix.
– The split tensile test findings indicate that a 10% replacement of cement will result in the maximum strength gain. Therefore, 10% is the ideal percentage for SCBA to replace the cement in the concrete. When 10% replacement of SCBA is used, the overall strength of the concrete's mechanical properties – compressive strength and tensile strength – increases by approximately 8–10% when compared to the control mix. The water absorption and porosity also increased with the increasing SCBA ratio.
– The RCPT values were found to be 'very low' for Mix 4 compared to the other mixes. Comparing SCBA-mixed concrete with the base mix, the 28-day RCPT value decreased by 54.6%. Likewise, it was determined that the 10% SCBA substitution enhanced the concrete's resistance to corrosion.
– It was observed that Mix 4 had carbonation of 2 mm at 28 days, while Mixes 1–3 had a 0-millimetre carbonation depth at 28 days. Additionally, it was observed that Mix 4 had carbonation of 2 mm at 7 days and 28 days. Finally, it was noted that the initial surface absorption test (ISAT) findings for Mixes 1, 2, and 3 were found to be reduced in comparison to Mix 4.

Authors' contributions

Conceptualisation and methodology: N.B.; investigation: N.B.; data curation: N.B.; writing – original draft preparation: N.B.; writing – review and editing: S.K.; visualisation: S.K.; project administration: S.K.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Amin, M., Tayeh, B. A. & Agwa, I. S. (2020). Effect of using mineral admixtures and ceramic wastes as coarse aggregates on properties of ultrahigh-performance concrete. *Journal of Cleaner Production*, *273*, 123073. https://doi.org/10.1016/j.jclepro.2020.123073

American Association of State Highway and Transportation Officials [AASHO] (2011). *Standard method of test for surface resistivity indication of concrete's ability to resist chloride ion penetration* (AASHTO TP 95). AASHTO. Retrieved from https://www.transportation.org

ASTM International [ASTM] (2010). *Standard test method for electrical indication of concrete's ability to resist chloride ion penetration* (ASTM C 1202-10). ASTM International. Retrieved from https://www.astm.org

ASTM International [ASTM] (2022). *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete* (ASTM C618-22). ASTM International. Retrieved from https://www.astm.org

Balakrishna, M., Mohamad, F., Evans, R. D. & Rahman, M. (2018). Assessment of water absorption of concrete by Initial surface absorption test. *Engineering, Environmental Science, Materials Science.*

British Standards Institution [BSI] (1996). *Testing of concrete. Part 208: Recommendations for the measurement of hardened concrete by ultrasonic pulse velocity* (BS 1881-208:1996). British Standards Institution. Retrieved from https://www.bsigroup.com

Bureau of Indian Standards [BIS] (2000). *Code of practice for plain and reinforced concrete* (IS 456:2000). Bureau of Indian Standards. Retrieved from https://www.bis.gov.in

Bureau of Indian Standards [BIS] (2015). *Ordinary Portland Cement – Specification* (IS 269:2015). Bureau of Indian Standards. Retrieved from https://www.bis.gov.in

Bureau of Indian Standards [BIS] (2016). *Specification for coarse and fine aggregates for concrete* (IS 383:2016). Bureau of Indian Standards. Retrieved from https://www.bis.gov.in

Bureau of Indian Standards [BIS] (2019). *Concrete mix proportioning – guidelines* (IS 10262:2019). Bureau of Indian Standards.

Chi, M. (2012). Effects of sugar cane bagasse ash as a cement replacement on properties of mortars. *Materials Science, Engineering, Environmental Science*, 279–285. https://doi.org/10.1515/SECM-2012-0014

Cordeiro, G. C., Andreão, P. V. & Tavares, L. M. (2019). Pozzolanic Properties of Ultrafine Sugar Cane Bagasse Ash Produced by Controlled Burning. *Heliyon*, *5* (10), e02566. https://doi.org/10.1016/j.heliyon.2019.e02566

Heniegal, A. M., Ramadan, M. A., Naguib, A. & Agwa, I. S. (2020). Study on Properties of Clay Brick Incorporating Sludge of Water Treatment Plant and Agriculture Waste. *Case Studies in Construction Materials*, *13*, e00397. https://doi.org/10.1016/j.cscm.2020.e00397

Jha, P., Sachan, A. K. & Singh, R. P. (2021). Bagasse Ash (ScBa) and Its Utilization in Concrete as Pozzolanic Material: A Review. *Lecture Notes in Civil Engineering*. https://doi.org/10.1007/978-981-33-6969-6_41

Joshaghani, A. & Moeini, M. A. (2018). Evaluating the Effects of Sugarcane-Bagasse Ash and Rice-Husk Ash on the Mechanical and Durability Properties of Mortar. *Journal of Materials in Civil Engineering*, *30* (7), 1943–5533. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002317

Mohammadinia, A., Arulrajah, A., D'Amico, A. & Horpibulsuk, S. (2018). Alkali-activation of fly ash and cement kiln dust mixtures for stabilization of demolition aggregates. *Construction and Building Materials*, *186*, 71–78. https://doi.org/10.1016/j.conbuildmat.2018.07.103

Olufemi, F. S. (2017). Initial Surface Absorption of Cement Combination Concretes Containing Portland Cement, Fly Ash, Silica Fume and Metakaolin. *International Journal of Sustainable Construction Engineering & Technology*, *8* (2). https://doi.org/10.9744/ced.20.2.96-101

Rahimah, E., Nasir, S. & Kusbiantoro, A. (2015). Silica Extraction and Incineration Process of Sugarcane Bagasse Ash (ScCBA) as Pozzolanic Materials: A Review. *Journal of Materials in Civil Engineering*, *V11*, 7304–7308.

Ramasamy, V. (2012). Compressive Strength and Durability Properties of Rice Husk Ash Concrete. *KSCE Journal of Civil Engineering*, *16*, 93–102. https://doi.org/10.1007/S12205-012-0779-2

Thomas, B. S., Yang, J., Bahurudeen, A., Abdalla, J. A., Haweeleh, R. A., Hamada, H. M., Nazar, S. V. J. & Ashish, D. K. (2021). Sugarcane Bagasse Ash as Supplementary Cementitious Material in Concrete – A Review. *Materials Today Sustainability*, *V15*. https://doi.org/10.1016/j.mtsust.2021.100086

Zeyad, A. M., Johari, M. M. A., Tayeh, B. A. & Yusuf, M. O. (2016). Efficiency of Treated and Untreated Palm Oil Fuel Ash as A Supplementary Binder on Engineering and Fluid Transport Properties of High-Strength Concrete. *Construction and Building Materials*, *125*, 1066–1079. https://doi.org/10.1016/J.CONBUILDMAT.2016.08.065

WŁAŚCIWOŚCI POPIOŁU Z WYTŁOKÓW Z TRZCINY CUKROWEJ Z AGROODPADÓW W TESTACH TRWAŁOŚCI

STRESZCZENIE

Przemysł betonowy coraz częściej włącza do produkcji materiały odpadowe takie jak popiół z wytłoków z trzciny cukrowej (SCBA) ze względu na jego doskonałe właściwości pucolanowe. Cement, kluczowy i rzadki składnik w produkcji betonu, jest bardzo poszukiwany na całym świecie. Rozwój sektora budowlanego w znacznym stopniu przyczynia się do emisji dwutlenku węgla (CO_2), co podkreśla potrzebę zmniejszenia zawartości cementu w betonie w celu złagodzenia tych emisji. Zastąpienie części cementu w betonie produktami ubocznymi rolnictwa, takimi jak łuski ryżowe i wytłoki z trzciny cukrowej, może znacznie zmniejszyć wpływ materiału budowlanego na środowisko przyrodnicze. W niniejszym badaniu zbadano trwałość betonu z SCBA jako częściowym zamiennikiem cementu na poziomach 5%, 10% i 15% wagowo. Trwałość betonu oceniono za pomocą kilku testów, w tym: rezystywności elektrycznej, tzw. szybkiej penetracji chlorków (RCPT), początkowej absorpcji powierzchniowej (ISAT) i karbonatyzacji po 7 dniach i 28 dniach. Zaobserwowano, że SCBA ma dobre właściwości wiążące i może być stosowany w mieszankach betonowych w celu częściowego zastąpienia kosztownego cementu.

Słowa kluczowe: agroodpady, popiół z trzciny cukrowej, trwałość, beton

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REVIEW PAPER

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PERFORMANCE OF AGRO-WASTE CEMENTITIOUS MATERIAL IN THE HIGH-STRENGTH REINFORCED CONCRETE APPLICATIONS: A REVIEW

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ABSTRACT

The rapid urbanisation and rising demand for high-performance concrete (HPC) have driven research towards sustainable, environmentally friendly, and cost-effective alternatives to traditional cement. Agricultural waste cementitious materials, such as fly ash, rice husk ash, and bagasse ash, have been used as cementitious material due to their pozzolanic properties. This review explores the feasibility of incorporating these agro-waste materials in high-strength reinforced concrete (HSRC) applications, focusing on their effects on the durability, sustainability and mechanical properties of concrete. Previous studies indicate that the partial replacement of cement (5–10%) with such waste materials can enhance the mechanical strength due to the additional calcium silicate hydrate (C-S-H) gels, which improve its microstructural densification. Moreover, this material's fineness improves the durability by reducing its permeability, enhancing the sulphate and chloride resistance, and mitigating the alkali-silica reaction (ASR). Utilising agricultural waste also significantly lowers the related carbon emissions, minimises industrial waste disposal, and promotes sustainable construction practices. However, challenges such as the variability of the chemical composition, proper processing (grinding and calcination), and standardisation issues must be addressed for broader implementation. This review provides a comprehensive analysis of agro-waste cementitious materials in HSRC, highlighting their benefits and limitations while emphasising the need for further research to optimise their performance and reliability in structural applications.

Keywords: fly ash, rice husk ash, bagasse ash, durability, sustainability, concrete

INTRODUCTION

For almost two centuries, portland cement has been utilised as a binder in concrete and other concrete--related uses. As its use has been increasing in demand over time, its production has also increased, which has inevitably resulted in environmental issues (Gupta & Kashani, 2021). Globally, 8–10% of carbon dioxide (CO_2) emissions are attributed to the manufacturing of cement, which is a cause of many environmental problems. Future increases in cement production will increase atmospheric CO_2 (Poudyal & Adhikari, 2021). The environmental issues associated with cement manufacturing make it necessary to use a variety of industrial and agricultural by-products to reduce the quantity of CO_2 released into the atmosphere. Utilising these types of by-products will increase the development of industrial products as well as sustainable agriculture for

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the global market and lessen the amount of industrial and agricultural trash that is dumped (Jittin, Rithuparna, Bahurudeen & Pachiappan, 2020).

This study was inspired by the widely available and reasonably priced agro-waste as sustainable and workable materials. The data show that in industrialised and developing nations, biomass makes up only 9% to 14% of energy sources (Khan, De Jong, Jansens & Spliethoff, 2009). Studies are being conducted to comprehend the diverse properties of binders from different industrial and agricultural wastes. Due to their high silica content, industrial-agro waste materials like silica fume (SF), ground granulated blast furnace slag (GGBS), bagasse ash (BA), fly ash (FA), rice husk ash (RHA), and waste ash derived from coconuts are widely used in concrete and have been for a few decades. Studies on the usage of a few of the aforementioned by-products have shown that they have several benefits, including improved strength and durability, reduced construction costs due to the use of less cement, decreased carbon dioxide emissions, which benefits the environment, and easier disposal of industrial-agro-waste materials that would otherwise pollute the environment (Thomas et al., 2018). According to Figure 1a, the total amount of garbage produced and cement produced worldwide each year is 4.01 billion and 2.02 billion tonnes, respectively, and both are expected to increase in the upcoming years (Kaza, Yao, Bhada & Woerden, 2018). As seen in Figure 1b, of these waste materials, 44% comes from food and agricultural wastes, while the remaining 56% comes from industrial and other wastes (Kaza et al., 2018).

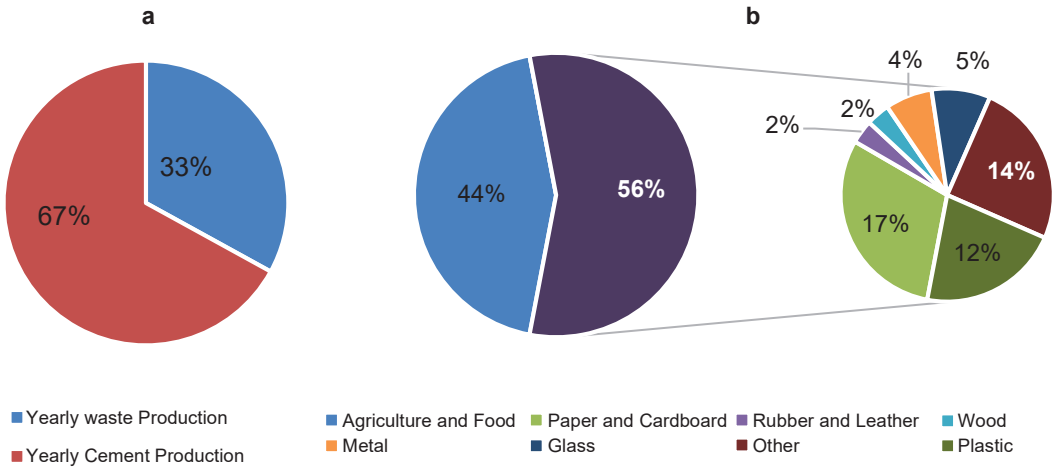


Fig. 1. Waste globally: a – comparison of worldwide production of waste and cement, b – classifications of waste product

Source: Zhang et al. (2015).

About 45.2 million tonnes of ash generated by sugarcane and 30.6 million tonnes of maise stalk ash are produced annually, with the remainder coming from various agricultural and food wastes, as illustrated in Figure 2b. The use of industrial wastes in manufacturing concrete has been the focus of multiple research investigations, both past and present. Reducing or reusing the quantity of waste produced by the industrial and agricultural sectors could be achieved using waste derived from agro-industrial processes in the building sector, which would also offer a long-term solution to the issues brought on by agro-industrial waste disposed of in landfills (Hemlatha & Ramaswamy, 2017). Due to their abundance, these by-products from the agricultural and industrial sectors can be used with cement in the construction industry for less expensive

small-scale building projects like grouting, interlocks, plastering, and constructing walkways. It can be used as a substitute for cement in alkali-activated slag mortars or used to replace natural coarse aggregate with greater strength and durability (Zhang et al., 2015). The main disadvantage of using these materials is that they absorb water more quickly due to their vast surface area. Other drawbacks include handling alkali--activating materials poorly, working with large-scale practical applications poorly, and burning wastes to improve their reactivity.

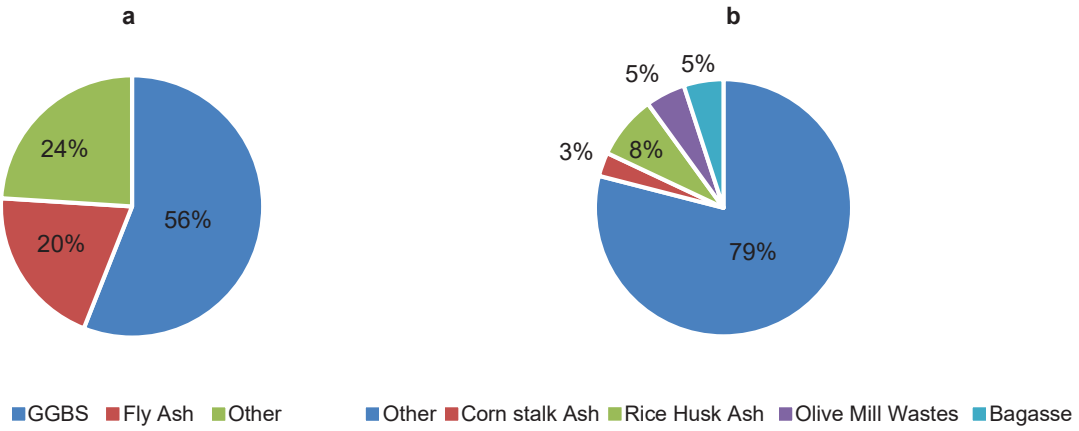


Fig. 2. Wastes: a – produced industrial waste, b – agricultural and food wastes

Source: Kumar, Yaragal and Das (2020).

Burning agro-waste is a significant environmental problem because it negatively affects air quality and risks public health (Bie, Song, Liu, Ji & Chen, 2014). Calcined wastes can improve reactive materials in various ways, depending on the type of waste and its composition, which tends to enhance the pozzolanic properties and aids in optimising the amorphous silica that is already present (Sultana & Rahman, 2013). In contrast, uncalcined waste ashes have a more significant carbon content than calcined ash and are more likely to be in the amorphous phase (Thomas et al., 2021). Consequently, the current review addresses the effects of pozzolanic processes on the characteristics of the binder system in both calcined and uncalcined states, in addition to investigating industrial and agro wastes such as supplementary cementitious materials (SCMs) and alkali-activated binders (AABs) materials.

INFLUENCE OF AGRO-INDUSTRIAL WASTES IN CONCRETE

In nations like China, India, and the US, the agricultural and industrial sectors are significant producers of waste by-products that are often disposed of in landfills (Vaičiukynienė, Nizevičienė, Kantautas, Kielė & Bocullo, 2021). A process called calcination, which occurs at temperatures between 700 and 900°C, converts the amorphous silica found in agricultural and industrial wastes into extremely reactive silica while keeping the ashes. Heating crystalline silica at 900°C yields non-reactive silica. When agricultural wastes are burned to produce biomass fuel, two types of ashes often form: biomass bottom ash (BBA) and biomass fly ash (BFA). Grinding this chemical more will enhance its surface area and reactivity. Adding different active

aluminosilicate elements to the blends is another way to increase the BBA precursor's reactivity (Sharma & Sivapullaiah, 2016). The two primary ashes that industries produce are fly ash and GGBS, which are further classified into groups based on the oxide compound and other characteristics (Kaniraj & Havanagi, 1999).

The leftover particles, known as fly ash (FA), from coal-fired power stations can be utilised as an SCM and to make AAB concrete. These are the aluminosilicate materials that, according to the ASTM C618-12a standard (ASTM International [ASTM], 2012), may or may not have a high concentration of calcium oxide. As a result, they are categorised as either Class C or Class F. While sub-bituminous coal containing between 50% and 70% of the components above is used to produce Class C FA, and bituminous coal containing a mixture of SiO_2, Al_2O_3, and Fe_2O_3 concentrations of more than 70% is used to produce the majority of Class F FA. According to the source, the principal chemical composition of the oxide components in Class F and Class C FA varies from highest to minimum values, as illustrated in Table 1. Fly ash is thought to be pozzolanic, with a specific gravity of about 2.15, and exhibits minimal self-hardening qualities when chemical activators like cement or lime are not present (Durdziński, Dunant, Ben & Scrivener, 2015). Fly ash's composition alone is insufficient to explain the behaviour of fly ash because the presence of crystalline or amorphous phases of FA impacts the reactivity of the FA (Hemlatha & Ramaswamy, 2017).

Table 1. Chemical composition of Class C and Class F fly ash

Class	Range	Chemical oxide [%]									
		TiO_2	MnO	SO_3	MgO	Na_2O	K_2O	Fe_2O_3	Al_2O_3	SiO_2	Cao
C FA	max	1.0	0.2	12.9	6.7	2.8	9.3	15.6	20.5	46.4	54.8
C FA	min	0.6	0.03	1.4	0.1	0.2	0.3	1.4	2.6	11.8	15.2
F FA	max	2.6	0.1	4.7	5.2	3.6	4.1	21.2	35.6	62.1	14.0
F FA	min	0.5	0.03	0.02	0.3	0.1	0.1	2.6	16.6	37.0	0.5

Source: ASTM C618-12a standard.

An Indian standard IS 1489:1991 (Bureau of Indian Standards [BIS], 1991) states that the maximum % of fly ash that can be used to make Portland pozzolana cement is 35%. In its natural state, FA cannot enhance the strength properties when used at a rate of more than 35% replacement. The FA-cement binder mix must be altered to increase its strength under such conditions to produce more hydration products (Sanchez & Sobolev, 2010). The modification involves utilising the alkali activation method and nano-modified fly ash in an FA-cement binder mix to speed up early-age hydration. By acting as the cement's nucleus, the nanoparticles quicken the hydration process, thicken the microstructure, and reduce the permeability by densifying the interfacial transition zone (ITZ) (Kalifa, Jalaa & Younes, 2015). The effects of the SiO_2/Al_2O_3 molar ratios (3.25, 3.37, 3.50, and 3.75) on the properties of the FA-based geopolymer with FA (78%, 85%, 92%, and 96%) were examined. The SiO_2/Al_2O_3 ratio of 3.37 yielded the highest compressive strength, primarily attributable to the Al_2O_3–SiO_2 bonding in the amorphous region, which made up a more significant portion of the geopolymer's microstructure. The fly ash does not produce its reactive crystalline phase until calcined. The slump value of concrete prepared by partial substitution with calcined fly ash falls significantly compared to uncalcined FA (Duchesne & Bérubé, 2001). The drop in slump is brought about by the calcined FA's finer particle sizes, which fill the pores in the concrete and increase its density (Fig. 3). However, as seen in Figure 4, the calcined FA's water absorption capacity is greater than that of the uncalcined FA.

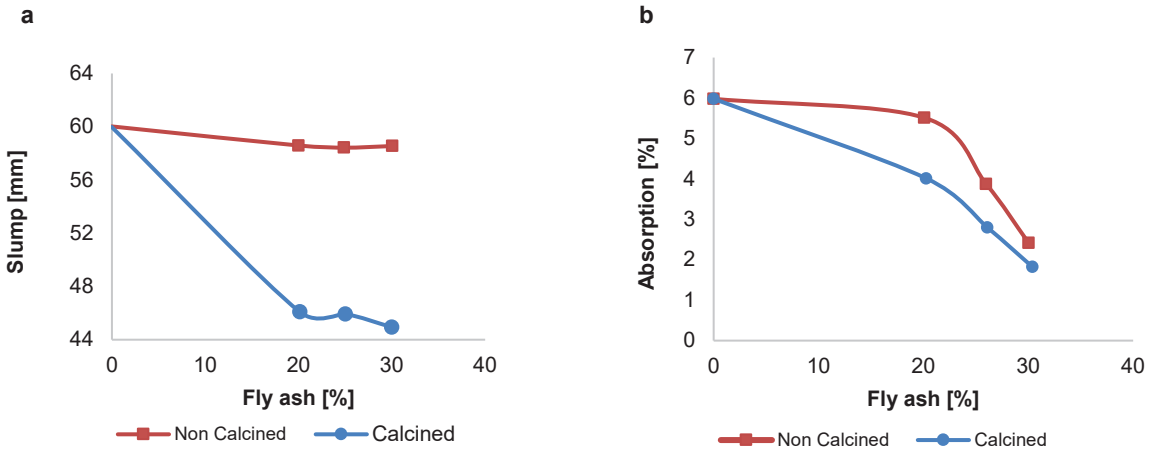


Fig. 3. Slump and water absorption ability of concrete on partial replacement with calcined (a) and uncalcined (b) fly ash

Source: Duchesne and Bérubé (2001).

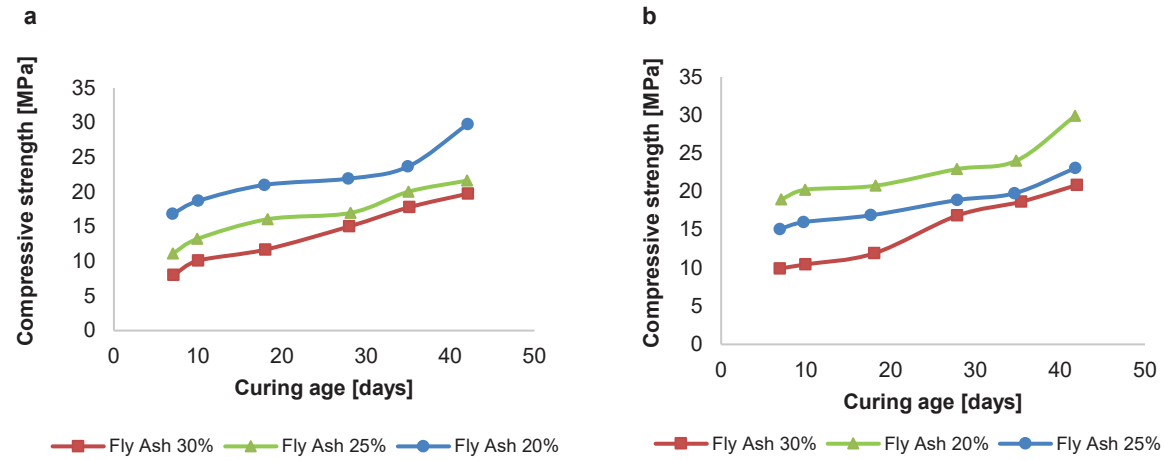


Fig. 4. Effect of partially replaced calcined (a) and uncalcined (b) fly ash on compressive strength

Source: own work.

The narrow pore structure of concrete made with fly ash contributes to its higher resistance to compressive force, hence an improvement in strength was noted regardless of whether calcined or uncalcined fly ash was employed as a partial replacement in the binder (Fig. 4). When compared to uncalcined fly ash, calcined fly ash has been shown to decrease the pore volume of fly ash–cement paste. All organic components are reduced or eliminated during the calcination of fly ash, which could have a negative or nonexistent effect on the strength of the concrete. Class C fly ash's variable and inferior durability to Class F fly ash is one of the key problems with utilising it in portland cement concrete. Class F fly ash has been shown in multiple experiments to be effective in attenuating the alkali-silica reaction; however, because of the lower alkali concentration, its efficacy is better at lower replacement rates (Thomas et al., 2011). Pore refinement, which lowers the permeability and increases the resistance to chloride, is seen in long-term durability investigations of fly ash-based geopolymer concrete.

Influence of rice husk ash in concrete

Rice husk ash is an excellent pozzolana material whose colour changes from black to white-grey based on the kind of incineration, temperature, and burning time (Ha Thanh, 2015). The grinding process determines its fineness; as the grinding energy and duration increase, the RHA's mean particle diameter decreases. Over the course of 0–540 min of grinding, the mean diameter of RHA particles in a ball mill drops from 86.2 to 5.7 μm (Singh & Singh, 2015). Because of its honeycomb structure, its specific surface area typically fluctuates between ten and a hundred times more than cement and five to ten times greater than silica fume. Adequately burnt RHA has Brunauer–Emmett–Teller (BET) values of 100–150 $m^2 \cdot g^{-1}$ (Tong et al., 2018).

A maximum specific surface area of 274 $m^2 \cdot g^{-1}$ can be attained if the RHA is treated. Numerous research demonstrates that RHA can be used to prepare a sodium silicate (Na_2SiO_3) solution and as a binder material. To improve the compressive strength and adequate setting time, fly ash and GGBS are often blended using this sodium silicate (Na_2SiO_3) solution as an alkali activator. Rice husk ash has a specific gravity that ranges from 2.1 to 2.6 and a particle size that varies from 5 μm to 96 μm (James & Rao, 1986). For isothermal heating to destroy the organic components from rice husk, a minimum temperature of 402°C is required to release the silica (Zareei, Ameri, Dorostkar & Ahmadiet, 2017). RHA generated the most reactive silica at a combustion temperature of 500°C.

Amorphous silica on the exterior of RHA particles is attacked by OH ions in the solution, which causes the silica to dissolve in the aqueous solution. The RHA particles absorb water due to the pores created when the amorphous silica dissolves. When silica in the solution combines with Ca and OH, C-(Na, K)-S-H gels are created. These precipitates can then absorb Na, K, and Al ions on the surfaces of RHA particles. Consequently, a pozzolanic reaction rim formation occurs, with RHA particles either fully or partially packed within the rim. The response rim thickens gradually.

Alkalis and silica interact to create alkali-silica reaction gels. These gels subsequently react with Ca ions, absorb water through the pores in RHA particles, and grow. The increasing alkali-silica reaction (ASR) hydrates and enhance the durability of concrete. The primary oxide components of RHA for both calcined and uncalcined rice husk ash (CRHA and URHA), as shown in Table 2, vary in value depending on the available source, from the maximum to the minimum.

Table 2. Chemical composition of calcined and uncalcined rice husk ash

Type	Range	Element oxide [%]									
		TiO_2	MnO	SO_3	MgO	Na_2O	K_2O	Fe_2O_3	Al_2O_3	SiO_2	CaO
CRHA	max	0.70	0.19	0.54	1.57	0.27	4.60	4.00	4.27	99.00	3.90
CRHA	min	0.04	0.11	0.01	0.07	0.10	0.31	0.07	0.06	88.00	0.25
URHA	max	0.70	0.10	0.70	0.80	0.44	5.10	3.90	0.68	82.00	0.92
URHA	min	0.02	0.02	0.01	0.07	0.11	1.66	0.07	0.01	73.68	0.16

Source: James and Rao (1986).

When preparing high-performance concrete, RHA, a pozzolanic reactive material, can be used to increase the surface area of the interfacial transition zone. When 25% of the cement is replaced with RHA, the mixed concrete becomes significantly more impermeable than regular concrete (Gastaldini, Isaia, Hoppe, Missau & Saciloto, 2009). Including rice husk ash (RHA) in geopolymer concrete with ultra-fine slag at room temperature resulted in a noticeable improvement in strength and durability.

The 28th-day and 91st-day compressive strengths of concrete in which 10%, 20%, and 30% of the cement were replaced with RHA are shown in Table 3. The increase in the 28-day compressive strength for concrete containing 10% RHA over the cement-based control concrete was between 15% and 27% for w/b ratios of 0.35, 0.50, and 0.65; on the 91st day, the increase was between 10 and 21%. On days 28 and 91, it was observed that the compressive strengths of 20% RHA concrete were 11–34% and 19–26%, respectively, while the values for 30% RHA concrete ranged from 6 to 26%, and 7 to 27%, respectively (Sathurshan, 2021).

Table 3. Compressive strength of concrete containing rice husk ash

Mixture	w/b ratio	Compressive strength [MPa]	
		after 28 days	after 91 days
Reference	0.35	54	67.9
	0.50	47	51.4
	0.65	28	35
10 RHA	0.35	68	76.4
	0.50	47	62.1
	0.65	32	38.6
20 RHA	0.35	72	85.6
	0.50	51.5	62.9
	0.65	32	41.7
30 RHA	0.35	67	78.9
	0.50	50	65.1
	0.65	30	37.3

Source: Saloni, Pham, Lim, Pradhan and Kumar (2021).

When 10% of the fine aggregate was replaced with unprocessed RHA and 15% with OPC, respectively, for 28 days, the highest compressive strengths of 81 MPa and 75 MPa were achieved (Athira et al., 2021). Except RHA, all other waste ashes often exhibit SiO_2 contents comparable to FA; this greater SiO_2 content helps binders manufactured from RHA build up early and remain exceptionally stable at high temperatures. More broadly, in metakaolin-based geopolymer systems, silica fume and RHA are essential for enhancing the freezing resistance and mechanical qualities of the material by enhancing the pore structure. When calcined RHA's fresh and hardened properties were compared to those of untreated (uncalcined and unground) RHA, it was discovered that calcined RHA had superior qualities while requiring more energy during preparation (Athira, Bahurudeen, Saljas & Jayachandran, 2021).

Influence of sugarcane bagasse ash in the concrete

A by-product of the sugar industry is sugarcane bagasse (SCB). During the sugar processing process, a significant amount of SCB is burned to produce sugarcane bagasse ash (SCBA) and electricity. According to Figure 5, which represents 46.3% of global sugarcane production in 2021, Brazil and India are the two biggest producers (Embong, Shafiq, Kusbiantoro & Nuruddin, 2016). Massive amounts of bagasse trash are accumulated in the landfill, and burned, and roughly 30% of it is turned into ash. Because bagasse ash meets cement's characteristics very well, it represents a significant substitute for cement. Thus, the goal of the current work is to provide a thorough analysis of the application of SCBA in helping SCMs create environmentally friendly concretes. SCBA is prepared by drying and then calcining (600–800°C), grinding, and sieving to form reactive silica. It affects the porosity and water absorption, and enhances concrete's mechanical

strength and workability depending on its dosage and fineness. SCBA serves as a sustainable pozzolanic material, improving performance and reducing waste.

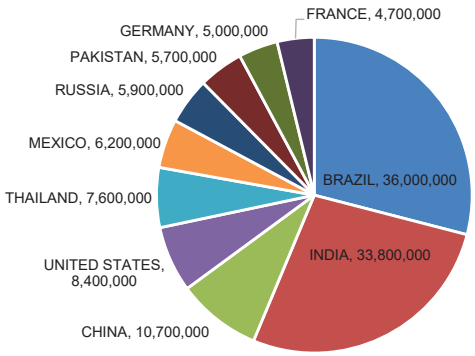


Fig. 5. Production of sugarcane bagasse in 2021 [thousand metric tonnes]

Source: Embong et al. (2016).

It was observed that burning SCB at temperatures between 600°C and 800°C results in SCBA with a large amount of amorphous silica, resulting in excellent pozzolanic qualities (Thomas, 2021). According to Embong et al. (2016), the ashes are determined by the degree and length of burning. Table 4 shows that the SiO_2 concentration rises with the increasing temperature and duration of burning up to 800°C for 2 h. The heating and cooling speeds were considered as $10°C \cdot min^{-1}$ and $1.67°C \cdot min^{-1}$, respectively. The agriculture waste (AW) was heated in a controlled drying oven for 2 h after reaching the necessary temperature (Salim, Ndambuki & Adedokun, 2014).

Table 4. Chemical composition of sugarcane bagasse ash after treatment

Temperature [°C]	Sample number	Chemical composition [%]									
		SiO_2	P_2O_5	CaO	K_2O	Al_2O_3	SO_3	MgO	Fe_2O_3	Na_2O	LOI
600	1	64.9	4.7	1.9	1.9	0.5	0.6	0.7	1.5	0.1	1.8
	2	74.8	6.2	2.1	2.6	2.2	0.7	1.2	0.4	0.3	0.5
	3	71.5	8.3	3.0	3.4	0.6	0.8	1.4	1.4	0.5	0.2
700	1	65.9	7.4	2.6	2.7	1.4	0.7	1.0	1.8	0.3	0.2
	2	72.0	5.9	2.2	2.5	1.0	1.0	1.2	1.4	0.2	0.2
	3	84.8	6.0	2.2	2.6	1.2	1.0	1.2	0.4	0.3	0.2
800	1	84.1	7.3	2.5	2.5	0.9	0.5	1.2	0.4	0.3	0.2
	2	84.3	5.6	1.9	2.9	1.1	0.5	1.4	1.7	0.3	0.1
	3	82.9	5.1	2.0	2.3	1.6	0.3	1.2	3.4	0.2	0.1

Source: Embong et al. (2016).

Table 4 presents the chemical composition of bagasse ashes derived from prior experiments. The collection process, grinding conditions, and treatment process were found to affect the chemical composition of the bagasse ashes.

DISCUSSION

The binding system utilising pozzolanic materials such as bagasse ash, fly ash or rice husk ash works better than any conventional cementitious materials in various respects. During the hydration process, calcium silicate hydrate (C-S-H) is formed, which is responsible for the strength, and calcium hydroxide ($Ca(OH)_2$) is formed, which does not contribute to the strength, but when the pozzolanic material reacts with [$Ca(OH)_2$], it produces additional C-S-H, which leads to long-term strength. While the cement produces the early strength, the pozzolonic materials contribute to a gradual increase in this strength, which makes the concrete stronger later on. The agricultural waste material's pozzolanic reaction refines the pore structure, and this property makes the material less permeable. The pozzolans reduce the alkali content in the concrete, which helps to mitigate the alkali-silica reaction (ASR) and prevent expansive gel formation. Cement production leads to CO_2 emissions, but pozzolanic materials reduce the total CO_2 emissions. Their use also increases waste utilisation, turning by-products (e.g., fly ash, bagasse ash) into valuable construction materials.

FUTURE SCOPE

Further research is required to finalise the optimal replacement percentage of agro-waste cementitious materials to achieve the maximum strength and durability properties, such as the shrinkage and creep behaviour of concrete containing agro-waste cementitious materials. There is a need to study concrete behaviours containing agro-waste in extreme environments (marine, industrial, and high-temperature conditions). There is also a lack of standardised testing methods and specifications for agro-waste-based cementitious materials, which limits their adoption in construction. A detailed life cycle assessment (LCA) should be conducted to determine the environmental benefits of agro-waste in high-strength concrete. Comparative studies on bonding behaviour with reinforcement and fire resistance properties are essential but have not been performed until now.

CONCLUSIONS

The current paper thoroughly evaluates earlier research studies and recent advancements in the use of agro-industrial wastes, industrial plant ashes, and agricultural farming wastes in concrete. The scientific community's task is to find a low-cost, durable, and high-quality building material for which several research studies have been carried out. These studies examine the properties of concrete that have been treated with ashes from agro-industrial waste as a pozzolanic addition. Following are the conclusions reached after looking over research projects that have been completed on agro-industrial wastes.

- It was observed that industrial wastes, including fly ash, provide excellent outcomes. Industrial wastes with smaller particle sizes have more significant surface areas, which would promote more vigorous bond formation in the AAB system.
- It was also observed that agro-based waste has a high concentration of silica, which makes the materials exhibit pozzolanic reactivity. This is advantageous for the growth of concrete's strength over time. It has been noted that a higher percentage of agro-based waste can substitute cement in concrete when there is better treatment, controlled burning, and enhanced particle refinement.
- A thorough review of the literature demonstrates that, while still retaining the necessary properties for building materials, fly ash, rice husk ash, and sugarcane bagasse waste ashes can be utilised as alternative activators in the AAB system or as pozzolanic materials in cement binder systems.
- It was also observed that using portland cement with substitutes of SCBA and RHA in the range of 5–10% by weight gives concrete exceptional mechanical qualities.

Authors' contributions

Conceptualisation and methodology: M.K.; investigation: S.K.; data curation: M.K.; writing – original draft preparation: M.K.; writing – review and editing: S.K.; visualisation: S.K.; project administration: S.K.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

ASTM International [ASTM] (2012). *Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete* (ASTM C618-12a). ASTM International.

Athira, V. S., Bahurudeen, A., Saljas, M. & Jayachandran, K. (2021). Infuence of diferent curing methods on mechanical and durability properties of alkali activated binders. *Construction and Building Material*, *299*. https://doi.org/10.1016/j.conbuildmat.2021.123963

Bureau of Indian Standards [BIS] (1991). *Specification for Portland pozzolana cement* (IS 1489:1991). Bureau of Indian Standards. Retrieved from https://www.bis.gov.in

Duchesne, J. & Bérubé, M. A. (2001). Long-term efectiveness of supplementary cementing materials against alkali-silica reaction. *Cement and Concrete Research*, *31* (7), 1057–1063. https://doi.org/10.1016/S0008-8846(01)00538-5

Durdziński, P. T., Dunant, C. F., Ben, M. & Scrivener, K. L. (2015). A new quantifcation method based on SEM-EDS to assess fy ash composition and study the reaction of its individual components in hydrating cement paste. *Cement and Concrete Research*, *73*, 111–122. https://doi.org/10.1016/j.cemconres.2015.02.008

Embong, R., Shafiq, N., Kusbiantoro, A. & Nuruddin, M. F. (2016). Effectiveness of low concentration acid and solar drying as pre-treatment features for producing pozzolanic sugarcane bagasse ash. *Journal of Cleaner Production*, *112* (1), 953–962. https://doi.org/10.1016/j.jclepro.2015.09.066.112

Gastaldini, A. L. G., Isaia, G. C., Hoppe, T. F., Missau, F. & Saciloto, A. P. (2009). Influence of the use of rice husk ash on the electrical resistivity of concrete: a technical and economic feasibility study. *Construction and Building Materials*, *23* (11), 3411–3419. https://doi.org/10.1016/j.conbuildmat.2009.06.039

Gupta, S. & Kashani, A. (2021). Utilization of biochar from unwashed peanut shell in cementitious building materials – effect on early age properties and environmental benefits. *Fuel Process Technology*, *218*, 106841. https://doi.org/10.1016/j.fuproc.2021.106841

Ha Thanh, L. (2014). *Behaviour of Rice Husk Ash in Self-Compacting High Performance Concrete*. F.A. Finger-Institut für Baustoffkunde, Bauhaus-Universität Weimar.

Hemalatha, T. & Ramaswamy, A. (2017). A review on fy ash characteristics – towards promoting, high volume utilization in developing sustainable concrete. *Journal of Cleaner Production*, *147*, 546–559. https://doi.org/10.1016/j.jclepro.2017.01.114

James, J. & Rao, M. S. (1986). Silica from rice husk through thermal decomposition. *Thermochim Acta*, *97* (C), 329–336. https://doi. org/10.1016/0040-6031(86)87035-6

Jittin, V., Rithuparna, R., Bahurudeen, A. & Pachiappan, B. (2020). Synergistic use of typical agricultural and industrial by-products for ternary cement: a pathway for locally available resource utilisation. *Journal of Cleaner Production*, *279*, 123448. https://doi.org/10.1016/j.jclepro.2020.123448

Kalifa, H. N., Jalaa, O. & Younes, Y. (2015). Effect of calcined and non calcined fly ash addition on the strength of concrete. *Journal of Kerbala University*, *13* (1), 141–148.

Kaniraj, S. R. & Havanagi, V. G. (1999). Compressive strength of cement stabilized fly ash-soil mixtures. *Cement and Concrete Research*, *29* (5), 673–677. https://doi.org/10.1016/S0008-8846(99)00018-6

Kaza, S., Yao, L., Bhada, P. & Woerden, F. (2018). What a waste 2.0 a global snapshot of solid waste management to 2050. Washington DC: The World Bank. https://doi.org/10.1596/978-1-4648-1329-0

Khan, A., De Jong, W., Jansens, P. & Spliethoff, H. (2009). Biomass combustion in fluidized bed boilers: Potential problems and remedies. *Fuel Processing Technology*, *90* (1), 21–50. https://doi.org/10.1016/j.fuproc.2008.07.012

Kumar, C., Yaragal, S. C. & Das, B. (2020). Ferrochrome ash e its usage potential in alkali activated slag mortars. *Journal of Cleaner Production*, *257*, 120577. https://doi.org/10.1016/j.jclepro.2020.120577

Poudyal, L. & Adhikari, K. (2021). Environmental sustainability in cement industry: An integrated approach for green and economical cement production. *Resources, Environment and Sustainability*, *4*, 100024. https://doi.org/10.1016/j.resenv.2021.100024

Salim, W., Ndambuki, J. & Adedokun, D. (2014). Improving the Bearing Strength of Sandy Loam Soil Compressed Earth Block Bricks Using Sugercane Bagasse Ash. *Sustainability*, *6* (6), 3686–3696. https://doi.org/10.3390/su6063686

Saloni, P., Pham, T. M., Lim, Y. Y., Pradhan, S. S., Jatin & Kumar, J. (2021). Performance of rice husk ash-based sustainable geopolymer concrete with ultra-fine slag and corn cob ash. *Construction and Building Materials*, *279*, 122526. https://doi.org/10.1016/j.conbuildmat.2021.122526

Sanchez, F. & Sobolev, K. (2010). Nanotechnology in concrete – a review. *Construction Building Material*, *24* (11), 2060–2071. https://doi.org/10.1016/j.conbuildmat.2010.03.014

Sathurshan, M. (2021). Untreated rice husk ash incorporated high strength self-compacting concrete: properties and environmental impact assessments. *Environmental Challanges*, *2*, 100015. https://doi.org/10.1016/j.envc.2020.100015

Sharma, A. K. & Sivapullaiah, P. V. (2016). Ground granulated blast furnace slag amended fy ash as an expansive soil stabilizer. *Soils and Foundations*, *56* (2), 205–212. https://doi.org/10.1016/j.sandf.2016.02.004

Singh, J. & Singh, H. (2015). A review on utilization of rice husk ash in concrete. *International Journal of Innovations in Engineering Research and Technology* [*IJIERT*], *2* (11), 1–7.

Sultana, M. S. & Rahman, A. (2013). Characterization of calcined sugarcane bagasse sugarcane waste ash for industrial use. Conference. *International Conference on Mechanical, Industrial and Materials Engineering 2013 (ICMIME2013*), *1–3*, 508–513.

Thomas, B. S. (2018). Green concrete partially comprised of rice husk ash as a supplementary cementitious material – a comprehensive review. *Renewable and Sustainable Energy Reviews*, *82* (3), 3913–3923. https://doi.org/10.1016/j.rser.2017.10.081

Thomas, M. (2021). The effect of supplementary cementing materials on alkali-silica reaction: a review. *Cement and Concrete Research*, *41* (12), 1224–1231. https://doi.org/10.1016/j.cemconres.2010.11.003

Thomas, B. S., Yang, J., Bahurudeen, A., Abdalla, J. A. & Ashish, D. K. (2021a). Sugarcane bagasse ash as supplementary cementitious material in concrete – a review. *Materials Today Sustainability*, *15* (100086). https://doi.org/10.1016/j.mtsust.2021.100086

Thomas, B. S., Yang, J., Hung, K., Abdalla, J. A., Hawileh, R. A. & Ariyachandra, E. (2021b). Biomass ashes from agricultural wastes as supplementary cementitious materials or aggregate replacement in cement/geopolymer concrete: a comprehensive review. *Journal of Building Engineering*, *40*, 102332. https://doi.org/10.1016/j.jobe.2021.102332

Vaičiukynienė, D., Nizevičienė, D., Kantautas, A., Kielė, A., & Bocullo, V. (2021). Alkali activated binders based on biomass bottom ash and silica by-product blends. *Waste Biomass Valoriz*, *12* (2), 1095–1105. https://doi.org/10.1007/s12649-020-01042-0

Zareei, S. A., Ameri, F., Dorostkar, F. & Ahmadi, M. (2017). Rice husk ash as a partial replacement of cement in high strength concrete containing micro silica: evaluating durability and mechanical properties. *Case Study in Construction Material*, *7*, 73–81. https:// doi.org/10.1016/j.cscm.2017.05.001

WYDAJNOŚĆ MATERIAŁU CEMENTOWEGO Z AGROODPADÓW W ZASTOSOWANIACH ŻELBETOWYCH O DUŻEJ WYTRZYMAŁOŚCI: PRZEGLĄD

STRESZCZENIE

Szybka urbanizacja i rosnące zapotrzebowanie na beton o dużej wydajności (HPC) skłoniły do badań nad zrównoważonymi, przyjaznymi dla środowiska i opłacalnymi alternatywami dla tradycyjnego cementu. Materiały cementowe z odpadów rolniczych, w tym popiół lotny, popiół z łusek ryżowych, popiół z wytłoków z trzciny cukrowej, ze względu na swoje właściwości pucolanowe coraz częściej są wykorzystywane w budownictwie. W niniejszym przeglądzie zbadano wykonalność integracji tych agroodpadów z zastosowaniami betonu zbrojonego o dużej wytrzymałości (HSRC), z uwzględnieniem

wpływu na trwałość, rozwój zrównoważony i właściwości mechaniczne. Poprzednie badania sugerują, że częściowe zastąpienie cementu tymi materiałami odpadowymi (na poziomie 5–10%) może zwiększyć wytrzymałość mechaniczną betonu, dzięki obecności dodatkowych żeli hydratycznych krzemianu wapnia (C-S-H), które poprawiają jego gęstość mikrostrukturalną. Ponadto rozdrobnienie tych materiałów przyczynia się do lepszej trwałości poprzez zmniejszenie przepuszczalności, zwiększenie odporności na siarczany i chlorki oraz złagodzenie reakcji alkaliczno-krzemionkowej (ASR). Utylizacja odpadów rolniczych odgrywa również znaczącą rolę w zmniejszaniu emisji dwutlenku węgla, minimalizowaniu utylizacji odpadów przemysłowych i promowaniu zrównoważonych praktyk budowlanych. Pozostają jednak wyzwania, w tym zmienność składu chemicznego, potrzeba właściwego przetwarzania (mielenie i kalcynacja) oraz kwestie związane ze standaryzacją, które należy rozwiązać w celu szerszego wdrożenia. Niniejszy przegląd zawiera kompleksową analizę materiałów cementowych z odpadów rolniczych w HSRC, w której podkreślono zarówno ich zalety, jak i ograniczenia, jednocześnie zwrócono uwagę na potrzebę dalszych badań w celu optymalizacji ich wydajności i niezawodności w zastosowaniach konstrukcyjnych.

Słowa kluczowe: popiół lotny, popiół z łusek ryżowych, popiół z wytłoków z trzciny cukrowej, trwałość, rozwój zrównoważony, beton

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IMPROVING THE QUALITY OF PETROL FUEL FOR INTERNAL COMBUSTION ENGINES

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ABSTRACT

The design of an automobile electromagnetic vibration cavitator created for the cavitation treatment of water-petrol fuel is described. Its use will allow not only saving fuel, but also increasing the completeness of combustion of the water-petrol fuel mixture; in other words, it will contribute to improving the environment. An experimental study of effectiveness of the fuel mixture cavitation treatment was carried out using A95 petrol and distilled water for automobile internal combustion engines. Cavitation treatment of the fuel mixture with a water-to-petrol ratio of 17 to 83% allows for an increase in the savings of expensive petrol by 15–20% during the operation of engines on flat and downhill roads and in city traffic jams. At the same time, the engine power is reduced by only 6–7% due to the cavitation treatment.

Keywords: fuel, petrol, water, cavitation disturber, electromagnetic drive, combustion completeness

INTRODUCTION

The development of automobiles with an electric drive does not eliminate the need to improve automotive internal combustion engines. Petrol engines will be used for a long time to drive large-tonnage vehicles, particularly special military equipment, as well as for motorised household devices. Therefore, research into operational characteristics of petrol engines will remain relevant.

The studies aimed at protecting the environment will always be of utmost importance, in particular the studies into reducing the level of emissions caused by incomplete combustion of engine fuel to the maximum extent possible. After all, incomplete combustion of fuel in engine cylinder chambers is the main cause of the harmful carbon dioxide, which leads to the 'greenhouse effect' and environmental pollution.

The vast majority of scientific studies aimed at improving the quality of automotive engine fuel and its complete combustion have focused on finding additives that promote combustion, primarily based on bioethanol (Phuangwongtrakul, Wechsatol, Sethaput, Suktang & Wongwises, 2016; Abikusna, Sugiarto,

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Monasari & Yamin, 2018). A rather progressive direction has emerged towards creating new fuel mixtures, in particular by adding ethanol (Liu, Wang, Long & Wang, 2015; Catapano, Sementa & Vaglieco, 2016) or alcohols (Wang, Liu, Long, Wang & He, 2015) to the main petrol mass. However, according to the results of these studies, this approach significantly increases the final cost of fuel. Therefore, it is more suitable for specialised automotive transport such as race cars.

There is a more economically viable approach focused on direct physical or physico-chemical influences on automotive fuel that improve its characteristics, particularly combustion completeness. Among physical influences on fuel, ultrasonic treatment has proven to be the most effective method of preventing diesel fuel from losing its fluidity at low temperatures (Mysyura, 2018).

Along with the quality of petrol, the injection of the air-fuel mixture into the working chamber has a decisive influence on the completeness of fuel combustion in the working chamber of the cylinders of internal combustion engines. Insufficient completeness of combustion is caused predominantly by insufficient oxygen in the air-fuel mixture. At the same time, the dispersion degree of the fuel provided by the carburettor or injection nozzles is also important. The higher the dispersion of the petrol fed into the combustion chamber, the better it mixes the with air (Lugovskoi, 1997). The better the conditions for fuel complete combustion, the higher the power of the engine and the lower the degree of environmental pollution (Lugovskoi, 1998).

The scientists of the National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute" have proposed cavitation ultrasonic devices for increasing the dispersion of the air-fuel mixture injected into the working chambers of engine cylinders (Lugovskoi, 2000). Their operating principle is based on dispersing jets of fuel via vibrating dispersers at ultrasonic frequencies. This is done immediately before the air-fuel mixture enters the engine's combustion chamber (Lugovskoi, Chopny & Epemenko, 1998). The authors claim that ultrasonic cavitation treatment of fuel improves its energy and consumption characteristics. This is ensured by the following: as the cavitation bubbles in the microvolumes burst, high temperatures and pressures develop, which create prerequisites for the emergence of electric charges, whose significant energy is provided by dissociated and ionised molecules as well as atoms and free radicals, which improves the fuel combustion process (Lugovsky, Chorny & Eremenko, 1997; Chorny, Lugovsky & Prilipko, 2001). The authors claim that this process increases the power of engines by 10–15% without significantly increasing their dimensions and weight. In addition, it allows for a reduction in the level of emissions of the harmful carbon dioxide into the atmosphere by almost a quarter.

Also, under the leadership of Professor I.M. Fedotkina, a study of the effect of cavitation on fuel quality was conducted. Theoretical and experimental studies have shown quite good results (Fedotkin & Nemchyn, 1984). In particular, the ability of cavitation to positively influence the improvement of fuel quality has been established. This is explained by the destructive effect of cavitation on fuel clots, as well as fuel degassing from non-combustible gases dissolved in it. At the same time, cavitation also promotes high-quality mixing of certain fuel fractions (Fedotkin, 1979; Fedotkin, 2000).

Various methods were used to improve the completeness of fuel combustion, in particular by admixing the air--fuel mixture fed into the working chamber of engines with certain proportions of distilled water. Under the influence of high combustion temperatures of carbon compounds, including petrol, water molecules break up, releasing several gases. Along with water vapour, a number of flammable gas compounds are formed in this process. Among them are combustible compounds of oxygen and hydrogen and their possible combinations. This is why, in the case of fires caused by the combustion of carbon compounds, in particular lubricants, diesel and petrol fuels, it is not recommended to use water as a fire extinguishing agent (Shevchuk, 2013; Shevchuk, 2014).

However, the main obstacle to the industrial implementation of this progressive idea is the still-unsolved problem of clear dosing ratios of petrol, water and air and ensuring their high-quality mixing.

The purpose of this study is to develop a design of a low-frequency vibration resonance device for cavitation treatment of the water-fuel mixture before it is fed to the combustion chambers of petrol engines.

The research tasks include:

- Creation of an experimental installation for low-frequency cavitation treatment of a water-petrol mixture as fuel.
- Development of a technological scheme for preparing the water-fuel mixture for automobile internal combustion engines.
- Development of the design of an automobile vibrocavitator for cavitation treatment of the water-fuel mixture or fuel before it is fed to the engine combustion chambers.
- Study of the influence of the percentage ratio of components in the water-petrol mixture on the stability of the internal combustion engine.

MATERIAL AND METHODS

The effect of cavitation treatment on operational characteristics of the water-petrol mixture was studied using the carburettor internal combustion engine of a VAZ-21083 vehicle. In the first stage, distilled water and A95 petrol were mixed in the working area of the experimental low-frequency vibro-resonance cavitator built according to predefined proportions. This mixture was subject to cavitation treatment for a fixed time. In the second stage, the water-petrol mixture processed in the cavitator was directed into the carburettor of the working car engine. Important parameters of the engine were recorded via the readings of the indicator devices on the car's dashboard.

The technological scheme of the experimental laboratory installation for the cavitation treatment of the water-petrol fuel mixture is shown in Figure 1. From the storage tanks (*1*, *2*), petrol and distilled water in certain percentage ratios are supplied by pumps to the working area of the vibrocavitator (*3*). After filling the working area of the cavitator with petrol and water, the regulating valves are closed (*4*). The closed network of circulation of the water-petrol mixture is opened with the regulating throttle (*5*). At the same time, the electromagnetic drive (*8*) of the vibrocavitator (*3*) and the pump (*7*) located in the storage tank (*6*) are started. The regulating throttles (*5*) and (*9*) ensure uniform circulation of the water-petrol mixture between the storage tank (*6*) and the working chamber of the cavitator. The technological cycle of cavitation treatment of the fuel mixture involves continuous circulation of the mixture between the storage tank (*6*) and the working area of the vibrocavitator (*3*), which ensures continuous mixing and cavitation treatment of petrol and water.

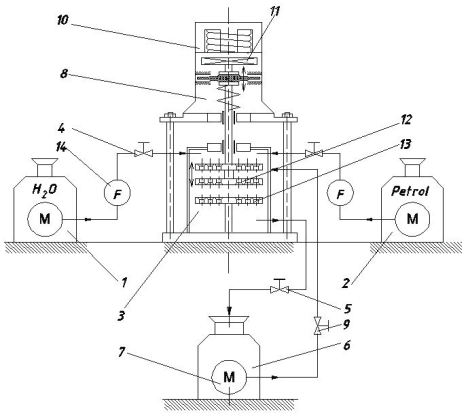


Fig. 1. Technological scheme of an experimental installation for mixing and cavitation treatment of a water-petrol mixture for internal combustion engines: *1*, *2* – storage tanks, *3* – vibrocavitator, *4* – valves, *5*, *9* – regulating throttle, *6* – tank, *7* – pump, *8* – electromagnetic drive, *10* – electromagnet, *11* – disc, *12*, *13* – cavitation disturbers, *14* – filters

Source: own work.

Cavitation treatment of the water-petrol mixture was carried out for 3–10 min. The variable parameters in the study were the percentage ratio between water and petrol in the fuel mixture, the duration of the treatment, and vibration parameters of the cavitation disruptors, namely their oscillation amplitude and frequency. The results of an experimental study of cavitation treatment of the water-petrol mixture are shown in Table 1.

Table 1. Research of cavitation treatment of a water-petrol mixture as fuel

Ratio of the components of the fuel mixture		Duration of cavitation treatment of the fuel mixture [s]	Vibration parameters of cavitation disruptors	
petrol [%]	distilled water [%]		oscillation frequency (f) [Hz]	amplitude (A) [mm]
95	5	90	48	1.0
90	10	86	45	1.1
85	15	80	50	1.2
83	17	75	52	1.0
80	20	70	47	1.2

Source: own work.

Field studies were conducted in the following sequence. A storage tank filled with a cavitationally processed water-petrol mixture was fixed above the car engine on a special device. A pipeline connected the storage tank to the engine carburettor, and the car engine was started at idle. Changes in the frequency of rotation of the crankshaft of the engine were observed on the instrument panel of the car using the tachometer readings. With the help of a timer, the amount of time required for the engine to burn a fixed amount of fuel mixture with a volume of 10^{-4} m^3 was monitored, observing the stability of engine operation when using the cavitationally treated water-petrol mixture as fuel. The results of the experimental study are shown in Table 2.

Table 2. Results of the study of automobile engine operation using a cavitationally treated water-petrol mixture as fuel

Ratio of petrol and water in the fuel mixture [%]	Engine crankshaft rotation frequency [min^{-1}]	Duration of engine operation per 10^{-4} m^3 of fuel mixture [s]	Engine stability
95/5	1,100	90	stable
90/10	1,050	86	stable
85/15	1,000	80	stable
83/17	970	77	unstable
80/20	950	75	with interruptions

Source: own work.

This experimental research established that the presence of up to 15% of distilled water in the cavitation-treated fuel does not significantly affect the stability of the car's engine in the 'idle' mode of operation. At the same time, the crankshaft rotation frequency is reduced by only 5–7%. It was also established that as the water content increases by 6–8%, the duration of engine operation on a fixed 10^{-4} m^3 volume of the fuel mixture is reduced.

Figure 2 shows the basic structural scheme of the automobile vibrocavitator. The function of this vibrocavitator is to cavitate petrol and form a water-petrol mixture as fuel. This vibrocavitator can be installed

directly into the engine. It is appropriate to use a standard voltage frequency regulator to power its electric drive, which is electrically connected to the car battery. The car's onboard computer can be tasked with regulating the vibrocavitator's operating modes and switching it on and off.

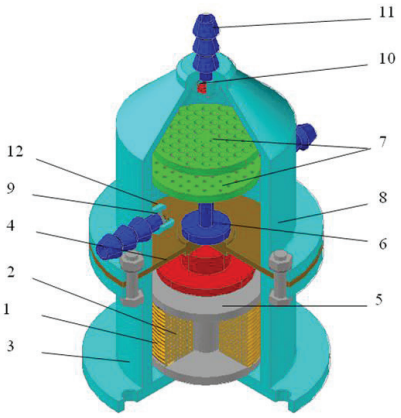


Fig. 2. Schematic diagram of a vibrocavitator for mixing water and petrol for an automobile engine: *1* – electromagnet, *2* – winding, *3* – housing, *4* – membrane, *5* – armature, *6* – rod, *7* – cavitation disturbers, *8* – cover of the housing, *9*, *12* – valves, *10* – spring plunger, *11* – fitting

Source: own work.

The components of the automobile vibrocavitator are an electromagnet (*1*) with a winding (*2*) rigidly fixed in the lower part of the housing (*3*). On the elastic membrane (*4*) above the electromagnet (*1*), the armature (*5*) of the electromagnet and the rod (*6*) are fixed. On this rod (*6*), the cavitation disturbers (*7*) are installed on the disk. Through the flanges, a cover is placed over the membrane (*4*) of the case and is hermetically connected to the lower part of the case (*3*), for example, with a bolted connection.

In the cover (*8*) of the housing (*3*), there are two inlet valves (*9*). For example, spring-loaded (*10*) petal valves. The inlets of the valves are equipped with a fitting (*11*) for connecting to the pipeline to supply water or petrol to the cavitator. On the upper part of the cover (*8*) of the housing, namely above the oscillating cavitation disturbers (*7*), there is an exhaust valve (*12*). This valve is connected through a fitting to the pipe connecting the cavitator to the car engine's carburettor or fuel distribution bar.

When applying the variable sinusoidal voltage transformed by the converter of the frequency regulator to the winding (*2*) of the electromagnet (*1*), the iron of the electromagnet is magnetised. Overcoming the elasticity of the membrane (*4*), the electromagnet attracts the anchor (*5*) to itself. Simultaneously with the anchor, the rod (*6*) rigidly connected to it moves along with the cavitation disruptors (*7*) attached to it. When the sinusoidal voltage of the electromagnet is reduced from its maximum value to zero, the elastic force of the elastic membrane (*4*) returns the anchor (*5*) to the original home location. At the same time, the rod (*6*) and the cavitation disruptors (*7*) are moved to the upper initial position simultaneously with the anchor. The spatial movements of the membrane (*4*), the anchor (*5*), the rod (*6*) and the cavitation disturbers (*7*) are repeated in a similar order in each subsequent half-cycle of the sinusoidal alternating voltage of the electromagnet winding. Finally, these movements are transformed into harmonic oscillatory motion of the armature (*5*) of the electromagnet and the cavitation disruptors connected to it. The frequency of these oscillating movements is equal to twice the frequency of the alternating voltage of the electromagnet winding.

It was established that the optimal modes of oscillatory movements of cavitation disruptors are the amplitude of 1.0–1.5 mm and the frequency between 47–52 Hz.

Figure 3 shows an updated technological scheme of a fuel preparation and supply network to the combustion chambers of the engine cylinders. A typical fuel supply network is equipped with a cavitator for processing the water-petrol mixture and a water supply subsystem with its regulation equipment. Like the traditional fuel supply scheme, the proposed one includes a storage tank (*1*), a petrol supply pump (*2*), a regulating throttle (*3*), and a filter (*4*). However, petrol is not supplied to the carburettor, but first to the cavitator (*5*). Through a similarly arranged network with a pump, a regulating throttle, and a filter a certain portion of distilled water is supplied to the cavitator from the additionally equipped storage tank (*6*). To ensure the predetermined percentage ratio of water and petrol in the fuel mixture, the amount of water supply is regulated by the adjusting throttle (*3*). The distilled water and petrol undergo cavitation treatment in the cavitator, mix with each other and are fed to the car's carburettor or distribution bar (*8*) through the outlet pipeline. As in the traditional fuel supply scheme, for example the fuel injection scheme, the water-petrol mixture formed in the cavitator (*5*) is saturated with air and enters the combustion chambers of the engine cylinders through the nozzles (*11*).

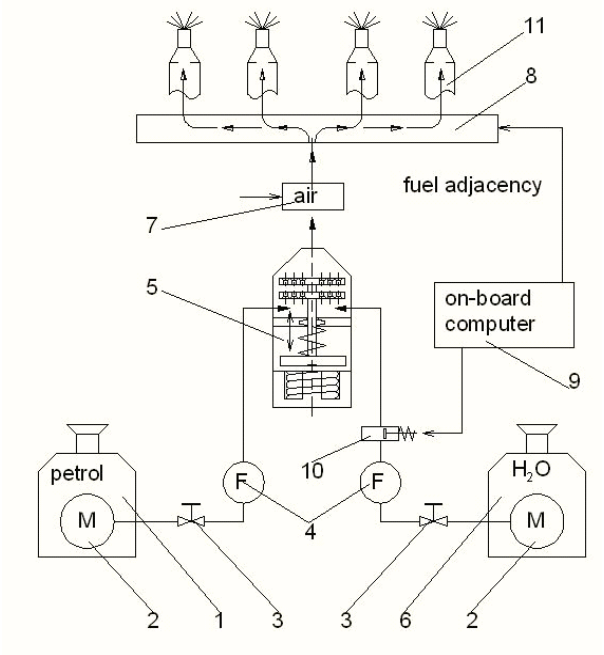


Fig. 3. Technological scheme of the network for preparation and supply of cavitated water-fuel mixture to the combustion chambers of the cylinders: *1* – storage tanks, *2* – pump, *3* – regulating throttle, *4* – filter, *5* – cavitator, *6* – tank, *7* – air, *8* – car carburettor, *9* – on-board computer, *10* – regulator, *11* – nozzles

Source: own work.

It is reasonable to predict that adding distilled water to the fuel mixture may decrease its torque and certain dynamic characteristics in difficult engine operating modes. Therefore, in cases of forced engine operation, it is advisable to temporarily switch off the water supply and return to the classic petrol supply scheme. In modern cars, it is advisable to entrust this function to the onboard computer (*9*), which will turn the water supply network's electric valve on and off (*7*) at certain moments of load changes.

RESULTS AND DISCUSSION

The main times of using the water-petrol mixture will be during 'light' modes of engine operation – the 'idle' mode, engine warm-up, driving on flat and sloping areas, etc. Most often, however, these are times of slow car movement in traffic jams that are prevalent in modern cities. In such relatively frequent traffic situations, it is critical to improve the modes of operation of automobile engines, because high expenditure of expensive fuel under the circumstances is inappropriate, whereas cheaper fuel mixtures, for example, the proposed water-petrol mixture semm to be a good replacement. Moreover, the saving of expensive petrol in the range of 10–15% is guaranteed to cover the costs of equipping cars with the proposed system for cavitating the water--petrol mixture (Aftanaziv & Shevchuk, 2022; Patent of Ukraine for Invention No. 125799).

Unlike previous studies by scientists in the field of physical effects on internal combustion engine fuel aimed at improving its properties, which were mainly focused on the use of various additives (Catapano et al., 2016; Phuangwongtrakul et al., 2016) and atomisation of microdroplets of fuel directed into the combustion chamber (Lugovskoi, 1997; Mysiura, 2018), this method of preliminary cavitation treatment of the water-fuel mixture has significant advantages.

First and foremost, it contributes to environmental protection by reducing petrol consumption by 15–17% and decreasing the release of extremely harmful combustion products into the atmosphere due to a higher level of combustion completeness. Another critical factor for vehicle users is the estimated 10–15% reduction in petrol expenses.

The results of experimental studies provide grounds to conclude that it is cavitation that contributes most to the improved combustion of the water-fuel mixture. Cavitational mixing of water and fuel promotes the formation of OH_1 radicals and hydrogen peroxide (H_2O_2) from the water. These substances possess high oxidative capacity, enhancing the mixture's combustion conditions in the engine's combustion chambers.

From a scientific perspective, the novelty of this study lies in the experimentally confirmed ability to induce cavitation processes and phenomena not only in homogeneous liquids, but also in water mixtures with the liquids that are difficult to mix with water, such as petrol.

The practical significance of this study is confirmed by the proposed new design of the vibrocavitator for preparing the water-fuel mixture in internal combustion engines, as well as the technological scheme for integrating it into the vehicle's fuel supply system. The novelty of these technical solutions is confirmed by the Ukrainian patent for the invention obtained by the co-authors of this study (Aftanaziv & Shevchuk, 2022; Patent of Ukraine for Invention No. 125799, 2022).

It is also advisable to consider the undeniable environmental benefit: a car equipped in this way will burn about 150 L of petrol less per year due to partial petrol replacement with water. This approximate figure is obtained from the calculation that the annual mileage of a passenger car is about 20×10^3 km on average, and half of this is spent on city trips and downtime in inevitable traffic jams, where the engine operates at low speed or in 'idle' mode. And for a city with a million inhabitants, where, according to statistics, there is one passenger car per every four residents, the environment will not be polluted by the combustion products of almost 18×10^6 L of petrol. This calculation conditionally considers that the number of cars with petrol and diesel engines in the city is approximately the same.

CONCLUSIONS

– Experimental research confirmed the possibility to use cavitation for intensive mixing of difficult-to-mix water and petrol at specific mass ratios. The water-petrol mixture produced by cavitation is suitable for ensuring stable operation of automobile engines in light modes, for example in the idle mode. The ratio range that provides stable operation of an engine is between 15–17% of water and 85–83% of petrol.

– It was experimentally established that when increasing the mass of water in a water-petrol cavitationally treated fuel mixture, the engine crankshaft rotation frequency decreases by 15–20%. A proportional decrease in its torque will accordingly decrease engine power.
– A working chamber with disc cavitation disruptors is the basis of the proposed design of the low-frequency vibro-resonant cavitator for mixing and cavitation treatment of the water-petrol mixture. Oscillating movements of the cavitation disruptors are forced by an electromagnetic drive powered by the car's battery. It was established that the optimal mode of oscillatory movements of the cavitation disruptors is an amplitude of 1.0–1.5 mm and a frequency of 47–52 Hz.
– The improved technological scheme for supplying a cavitationally treated water-petrol mixture as fuel to the cylinders of an internal combustion engine includes the addition of the traditional petrol supply network with an electromagnetic vibrating cavitator for mixing the water-petrol mixture and an additional water supply network with a storage tank.
– The 'light' modes of engine operation, in particular the idle mode, driving in city traffic jams, driving on straight and downhill roads etc., are the best times to use the water-petrol mixture.

Authors' contributions

Conceptualisation: I.A.; methodology: I.S.; validation: I.K.; formal analysis: I.S.; investigation: N.K.; resources: Y.R.; data curation: V.R.; writing – original draft preparation: I.A. and L.S.; writing – review and editing: I.A. and L.S.; visualisation: N.K.; supervision: R.H. and Y.S.; project administration: S.B.; funding acquisition: I.K.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Abikusna, S., Sugiarto, B., Monasari, R. & Yamin, I. (2018). The effect of additive on combustion characteristics and cycle to cycle variations on SI engine fueled by gasoline and bioethanol. Eastern-European *Journal of Enterprise Technologies*, *6* (6), 27–36. https://doi.org/10.15587/1729-4061.2018.147585

Aftanaziv, I. S. & Shevchuk, L.I. (2022). Patent of Ukraine for invention No. 125799 Method of cavitation preparation of fuel for internal combustion engines. *Bulletin*, *23* of 08.06.2022.

Catapano, F., Sementa, P. & Vaglieco, B. M. (2016). Air-fuel mixing and combustion behavior of gasoline-ethanol mixtures in a multi-cylinder optical GDI engine with turbocharging and wall control. *Renewable Energy*, *96*, 319–332. https://doi.org/10.1016/j.renene.2016.04.087

Chorny, V. I., Lugovsky, O. F. & Prilipko, Y. S. (2001). Device for ultrasonic heating of combustion engines in internal combustion engines. Patent No. UA 42827. *Bulletin*, *10* of 11.15.2001.

Fedotkin, I. M. & Nemchyn, A. F. (1984). *The use of cavitation in technological processes*. Kyiv: Higher school. Publishing House at Kyiv. University of Technology.

Fedotkin, I. M. (1979). *Intensification of technological processes*. Kyiv: Higher school. Main publishing house.

Fedotkin, I. M. (2000). Cavitation, cavitation equipment and technology, their use in industry (Theoretical foundations for the production of excess energy, calculation and design of cavitation heat generators). *JSC "GLAZ"*, *Part 11*, 898.

Liu, H., Wang, Z., Long, Y. & Wang, J. (2015). Dual fuel spark ignition (DFSI) burns using various alcohols and gasoline to save fuel. *Fuel*, *157*, 255–260. https://doi.org/10.1016/j.fuel.2015.04.042

Lugovskoi, A. F. (1997). Application of piezoelectric transducers as a way to improve fuel preparation and supply systems in internal combustion engines. *Bulletin of the National Technical University of Ukraine KPI. Mechanical Engineering*, *32*, 34–38.

Lugovskoi, A. F. (1998). Preparation of the fuel mixture in an internal combustion engine using ultrasound. Bulletin of the National Technical University of Ukraine KPI. *Mechanical Engineering*, *32*, 209–213.

Lugovskoi, A. F. (2000). Ultrasonic atomization in fuel-air mixture preparation systems. Engineering in agricultural production, industrial engineering, automation. *Collection of scientific works of the Kirovohrad State Technical University*, *7*, 30–33.

Lugovskoi, A. F., Chopny, V. I. & Epemenko, A. I. (1998). Preparation of the fuel mixture in the internal combustion engine fueling systems with the help of an ultrasonic disperser with radial-bending oscillations. Progressive engineering and technology of mechanical engineering, application development and coal production. *Proceedings of the International Scientific and Technical Conference*, *3*, 341–346.

Lugovsky, O. F., Chorny, V. I. & Eremenko, O. I. (1997). Improving the efficiency of the internal combustion engine for ultrasonic combustion processing. Current technologies in the aerospace complex. *Materials of the III International Scientific and Practical Conference*, 169–171.

Mysyura, M. I. (2018). Polipshennya ekspluatatsiynykh vlastyvostey dyzelnoho palyva v umovakh nyzkykh temperatur [Improving the operational properties of diesel fuel at low temperatures]. *Technical service of the agro-industrial, forestry and transport complexes*, *13*, 276–280. https://repo.btu.kharkov.ua//handle/123456789/5142

Phuangwongtrakul, S., Wechsatol, W., Sethaput, T., Suktang, K. & Wongwises, S. (2016). Experimental study of the characteristics of a spark-ignition engine for the optimal mixing ratio of fuels based on ethanol and gasoline. *Applied Thermal Engineering*, *100*, 869–879. https://doi.org/10.1016/j.applthermaleng.2016.02.084

Shevchuk, L. I. (2013). *Low-frequency vibro-resonant cavitators* (Monograph 376). Lviv: Publishing House of Lviv Polytechnic.

Shevchuk, L. I. (2014). *Cavitation. Physical, chemical, biological and technological aspects* (Monograph 176). Lviv: Lviv Polytechnic.

Wang, Z., Liu, H., Long, Y., Wang, J. & He, X. (2015). Comparative study of the combustion of dual-fuel spark mixtures of alcohol-gasoline and gasoline-alcohol (DFSI) for increased load and high fuel efficiency. *Energy*, *82*, 395–405. https://doi.org/10.1016/j.energy.2015.01.049

POPRAWA JAKOŚCI PALIWA BENZYNOWEGO DO SILNIKÓW SPALINOWYCH

STRESZCZENIE

W artykule opisano konstrukcję samochodowego elektromagnetycznego kawitatora wibracyjnego stworzonego do rozdrabniania kawitacyjnego paliwa wodno-benzynowego. Jego zastosowanie pozwoli nie tylko zaoszczędzić paliwo, lecz także zwiększyć stopień zupełności spalania mieszanki paliwowo-wodnej, czyli przyczyni się do poprawy stanu środowiska przyrodniczego. Przeprowadzono eksperymentalne badanie skuteczności rozdrabniania kawitacyjnego mieszanki paliwowej na bazie benzyny A95 i wody destylowanej do silników spalinowych samochodowych. Rozdrabnianie kawitacyjne tej mieszanki paliwowej przy stosunku procentowym woda/benzyna 17/83% pozwala zwiększyć oszczędność drogiej benzyny o 15–20% podczas pracy silników na płaskich i pochyłych odcinkach autostrad oraz w korkach miejskich. Jednocześnie moc silnika zmniejsza się tylko o 6–7% dzięki rozdrabnianiu kawitacyjnemu.

Słowa kluczowe: paliwo, benzyna, woda, zakłócacz kawitacji (kawitator elektryczny), napęd elektromagnetyczny, stopień zupełności spalania

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ORIGINAL PAPER

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JOINT APPLICATION OF THE FINITE ELEMENT METHOD AND ARTIFICIAL NEURAL NETWORK IN THE IDENTIFICATION OF PARAMETERS OF LAYERED PAVEMENT

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ABSTRACT

In this paper, an inverse analysis of the mechanical parameters of existing layered pavements was performed. An artificial neural network (ANN) was used to approximate the response of the numerical pavement model to the input parameters. Two methods were presented. In the first method, the ANN directly maps the inverse relationship between the pavement surface deflection and mechanical parameters. In the second method, the approximated model was used in the classical back-calculation of pavements by a procedure of minimising the differences between the model response (now a neural network) and field measurements obtained from the falling weight deflectometer (FWD) test. Only one parameter of each pavement layer, the Young's modulus, was identified. It was found that the identification is not unambiguous. This means a given pavement deflection can be observed with different sets of layer stiffness moduli. However, the average stiffness of the layers is always identified with high accuracy.

Keywords: artificial neural network, inverse problems, numerical model, parameter identification, falling weight deflectometer, field measurement

INTRODUCTION

The road pavement structure is made up of a set of layers whose task is to transfer the loads from the wheels of vehicles to the ground, while ensuring an adequate level of convenience and traffic safety. The most important performance characteristic in the Polish evaluation system is the bearing capacity of the pavement, i.e. it is the ability to bear loads from traffic. Assessment of the mechanical properties of the existing multi-layer pavements based on the non-destructive load test of the top surface is currently the most widely used method. They are determined on the basis of measured, by static or dynamic methods, vertical displacements (deflections) of the pavement structure under a known load. A standardised device called a falling weight deflectometer (FWD) is used to perform such a test. Floor deflections are then caused by the impulse load from the falling weight. They are then measured at several points using geophones (a maximum of nine geophones) mounted on a rigid support, as part of a special-purpose vehicle (Figs 1 and 2). This process has an impact character and, as a result, the recorded pavement displacement represents the dynamic response to the load. On the other hand, in design practice, static pavement models in the form of layered elastic half-spaces are

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most often used. In current practice, researchers use methods of transforming the displacements obtained from the dynamic test into their static substitutes (Ruta, Krawczyk & Szydło, 2015). This paper emphasises the evaluation of the use of ANNs to identify pavement parameters. The FWD test was the inspiration for the conducted numerical experiments. In this paper, theoretically calculated (for the assigned known elasticity moduli) displacements were used as 'experimental' pseudostatic data from the FWD test.



Fig. 1. Dynatest® – falling weight deflectometer

Source: own work.

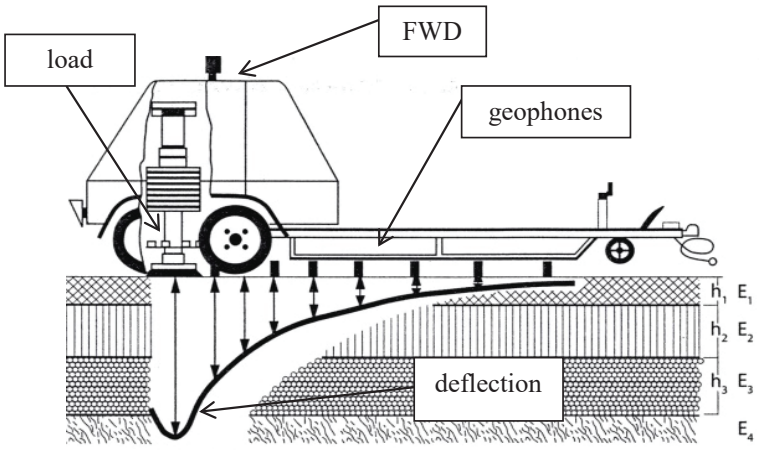


Fig. 2. Deflection bowl from FWD test

Source: Wesołowski and Blacha (2014).

A set of measured deflections is usually named the deflection bowl. These bowls are used in back analysis to identify parameters of computational models of road pavements. This process is called back calculation. The reaction of the pavement to the applied load, i.e. the measured deflections, determines the values of material properties that should be assigned to specified layers separately in the theoretical model of the pavement. As mentioned above, the theoretical model for the FWD test is usually an elastic layered half-space, statically loaded over a small area at the point of the falling mass (Yoder & Witczak, 1975; Ruta et al., 2015). In the case

of rigid pavements, the theoretical model may also be a layered plate supported on an elastic subgrade, e.g. the Winkler–Pasternak model (Boso & Lefik, 2012). Another method for the theoretical model of the pavement is a numerical formulation using, for example, the finite element method (FEM). The latter approach gives the greatest freedom of use in selecting the model parameters and has been used for the purposes of this article.

Classic backward calculations leading to the determination of the mechanical parameters of pavement layers consist in minimising the sum-of-squares differences between the measured and theoretical pavement deflections. Which can be written as follows:

$$\min_{p_i}\left[\sum_{k=1}^{m}\left(u_k\left(p_i\right)-d_k\right)^2\right], \tag{1}$$

where:
p_i – assumed parameters of the theoretical model,
i – layer index,
m – number of reading points,
$u_k(p_i)$ – calculated theoretical deflection at the k-th surface point,
d_k – measured deflection at the k-th surface point.

Any variables that have an influence on the solution can be model parameters, such as: elastic modules (Young's moduli) of layers E_j, Poisson's ratios v_j, layer thicknesses h_j, interface conditions between layers $k_{s,j}$ (j – layer index), and others. With the elastic formulation of the problem, assuming the continuity of the material between the layers and the assumed thickness of the pavement layers, only the moduli E_j have a significant influence on the deformation of the pavement system. Then, problem (1) can be written as follows:

$$\min_{E_j}\left[\sum_{k=1}^{m}\left(u_k\left(E_j\right)-d_k\right)^2\right]. \tag{2}$$

The optimisation problems mentioned above require frequent model evaluation when searching for the minimum of the objective function (calculation of deflections u_k). Depending on the complexity of the mechanical model, it can be a time-consuming process. Artificial neural networks (ANN) can be used as an input-output algorithm where the first set of data is the mechanical parameters of the pavement structure, and a second set of data is the mechanical response of the pavement under a known load, including measured deflections at given points on the pavement. When the first set is used as input data and the second set as output data, an ANN is being used as a numerical approximator that learns to simulate and solve the engineering problem. When the input data is the second dataset, and the output is the first set of data, the ANN is being used as a universal approximator of the inverse problem.

In this research, two alternative methods of searching for the optimal parameters of the FEM numerical model of the layered pavement will be presented and tested for the problem (2). Feed-forward artificial neural networks were used for both algorithms (Wojciechowski, 2011; Boso & Lefik, 2012; Lefik & Boso, 2016). This approach allows for a massive speed boost in solving the parameter identification problem and leads to better recognition of the inverse problem under consideration. ANNs have been previously used to solve the inverse problem of pavement mechanical properties identification (Meier, 1995; Bredenhann & Ven, 2004; Saltan & Terzi, 2005; Shahnazari, Tutunchian, Mashayekhi & Amini, 2012; Elbagalati, Elseifi, Gaspard & Zhang, 2017; Li & Wang, 2017; Li & Wang, 2018; Aubdulnibe & Jassim, 2019). In the literature on the subject, mostly examination of the first method is observed. The application and comparison of the two alternative approaches using the same ANN training and testing data is considered a main contribution of this paper.

ARTIFICIAL NEURAL NETWORKS

Artificial neural networks were based on the anatomical, physiological and biochemical knowledge of the human brain that was available at the time. However, the developers of neural networks treated this knowledge as a source of inspiration, not as a model to be copied exactly. Therefore, the construction and operating principles of artificial neural networks used in practice are not a faithful reflection of the state of biological knowledge, even that somewhat outdated knowledge from a dozen years ago. The first widely known example of a built and interestingly functioning neuro-like network is the 'Perceptron' (Minsky & Papert, 1969). The performance of the perceptron was not satisfactory from the point of view of the fundamental purpose of the test: although the system learned the task of recognition, it could not cope with more complex signs, and it showed sensitivity to changes in the scale of the learned objects. Despite the diverse architectures used by artificial neural networks, the essence of their operation is still based on the concept of the Perceptron algorithm, composed of a single artificial neuron.

The artificial neuron building blocks used in networks architecture are, of course, highly simplified models of nerve cells found in nature. The construction of an artificial neuron is best illustrated by the diagram shown in Figure 3.

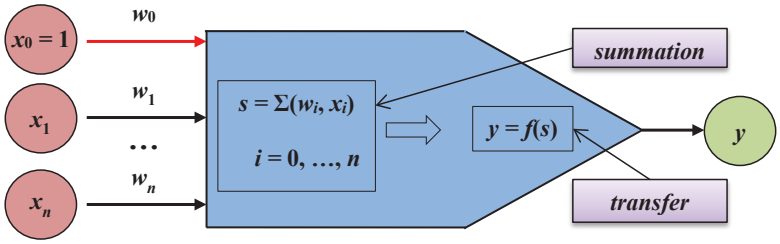


Fig. 3. Overall structure of a simplified neuron: basic signals, weighting coefficients, aggregation of data in the first internal function of the neuron, additional parameter – bias, transfer function

Source: own work.

Artificial neurons are characterised by the presence of multiple inputs and a single output. The input signals x_i ($i = 0, 1, 2, ..., n$) and the output signal y can take only numerical values, most often in the range from 0 to 1, while the fact that they correspond to certain unit of information in the tasks solved by the network is the result of a special procedure. Artificial neurons perform certain actions on the signals they receive at the inputs, as a result of which they produce signals (only one for each individual neuron), which are present at their outputs and are transmitted further (either to other neurons or to the output of the network, as a solution to the problem presented). Thus, the task of the network, reduced to the functioning of its basic element, which is the neuron, is that it transforms input information x_i into output y using rules derived from how it is built and what it has been taught. With each separate input of the neuron is an associated parameter called weight w_i. This name means that it expresses the degree of importance of the information reaching the neuron with this particular input. These weights reflect the rather complex biochemical and bioelectrical processes occurring in the real synapses of biological neurons. The most important thing is that synaptic weights can be modified (i.e. have their values changed), which is the basis of network learning. The signal coming in with a particular input is first modified using the weight of the input. The most common modification is that the signal is simply multiplied by the weight of the given input, so that it already participates in further calculations in a modified form. Sometimes (not in all types of networks, but generally often), some additional component independent

of the input signals is added, called a bias in the literature. Bias is also subject to a learning process. The bias signal is of a constant value of 1. The role of bias is that, thanks to its presence, the properties of the neuron can be shaped much more freely during the learning process. The addition of a bias value allows you to change the 0 point of the function. The input signals are aggregated inside the neuron, which most often means that the corresponding signals are simply summed. The result of this process gives some auxiliary internal signal called a net value. Such a sum can sometimes be directly transferred to the output and treated as the neuron's output signal. In more sophisticated networks, on the other hand, the output signal of a neuron is calculated using some nonlinear function, which is called a transfer function and usually is defined as $f(s)$ or $\varphi(s)$. The transfer function is commonly called the characteristics of the neuron. Various characteristics of the used activation functions are known: Sigmoid, threshold, linear, piecewise linear, threshold linear, Gaussian, tanh, and rectifying linear unit. The behaviour of the artificial neuron maximally resembles the behaviour of a real biological neuron (sigmoidal function), but they can be selected in such a way as to ensure maximum efficiency of the calculations carried out by the neural network.

So far, a single artificial neuron has been described. A neural algorithm is a network of artificial neurons organised in interconnected layers called an ANN. Such networks are built to eliminate the major drawback of the single neuron 'Perceptron' algorithm – the ability to classify only linear data. An example of a classical ANN is presented in Figure 4. At the beginning of the network is the input layer (LI), which, after receiving input signals x^0_i (i = 0, 1, 2, ..., n), generally does not process them but distributes them – which means that it distributes them to all the neurons x^j_i (i = 0, 1, 2, ..., n; j = 0, 1, 2, ..., k) of the hidden layers [with deep learning, the internal hidden layers (L1–LK) are observed]. Hidden layer neurons use the properties of a single artificial neuron described above. Thus, they process the input signal into an output signal y_i (i = 0, 1, 2, ..., n) and transmit it to the output layer (LO). In the classical ANN architecture, each neuron of the selected layer is connected to all neurons of the previous and next layers. This network architecture is often described as a feedforward structure. Feedforward networks are structures in which there is a well-defined direction of signal flow, from input to output on which the final result is given. Only during network training is the data flow reversed. Such networks are the most widely used and useful (Tadeusiewicz, 1993; Lefik & Schrefler, 2001; Shahin, Jaksa & Maier, 2001; Wojciechowski, Lefik, 2004; Boso, Lefik & Schrefler, 2012; Momeni, Nazir, Jahed Armaghani & Maizir, 2015; Alwattar & Mian, 2019; Vahab, Shahbodagh, Haghighat & Khalili, 2023). This type of network will also be used in this paper.

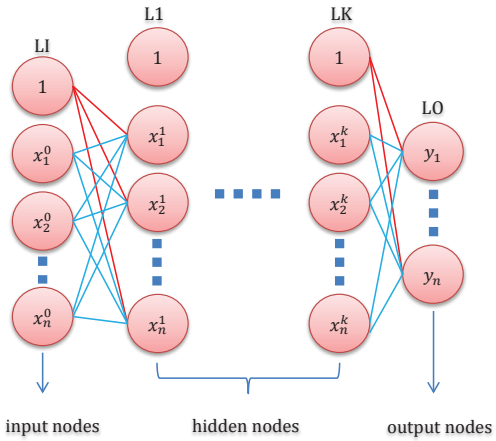


Fig. 4. Overall classical ANN architecture

Source: own work.

Training of the network is required so that it can correctly perform the operations intended for it. Training the ANN consists in finding the optimal values of the weights, so that the inputs belonging to the training data are processed and transmitted through the layers, resulting in outputs that fit well-known outputs (the ground truth) (Galbusera, Casaroli & Bassani, 2019). For training in the case of supervised learning, a set of labelled numerical data is used, divided into training, validation and testing subsets. The literature offers several proposals for dividing the dataset into the aforementioned subsets in different proportions. It is important that one data point can belong to one of the subsets. The training subset is used strictly to calculate weights with the use of backpropagation algorithms. The validation subset is used to adjust the net hyperparameters (e.g. learning rates, momentum). The test subset is used after the training process is completed, not for training the weights or adjusting the hyperparameters, but for assessing the model's accuracy and efficiency.

For many years, no effective method for training multilayer networks was known, which is why the layers for which the error signal could not be determined were known in the literature as 'hidden layers'. For this problem, the backpropagation algorithm turned out to be revolutionary. It consists of the fact that for the determined error $\delta^{(m)(j)}$ occurring during the j-th step of the learning process in an m neuron, we can project this error backwards to all neurons whose signal were inputs to the m neuron. The number of comparisons carried out depends on the size of the training set, the assumed number of iterations, and the training process of the network. This is because there are no specific guidelines to determine the weight parameters without testing the algorithm each time for a given problem.

NUMERICAL MODEL OF PAVEMENT

Formulation

The classical theory of an elastic half-space of a domain, e.g. a soil medium, describes the half-space as a homogeneous, infinite structure, limited on one side by a plane – the terrain surface. The layered half-space is a structure composed of many layers with different mechanical properties and separated by planes parallel to the surface of the terrain. For a pavement structure, the typical direction is horizontal. Typical examples of layered structures are the pavements of airports, roads, highways, and parking lots, supported on a subgrade. The general model of the pavement supported on the ground is shown in Figure 5. Each layer has an infinite size in the horizontal direction and is defined by a finite thickness h_j, Young's modulus E_j and Poisson's ratio v_j, where $j = 1, ..., n$ defines the number of the next layer. The last layer is described by the modulus of elasticity E_n and Poisson's ratio v_n and it has an infinite size in both the horizontal and vertical directions ($h_n \rightarrow \infty$).

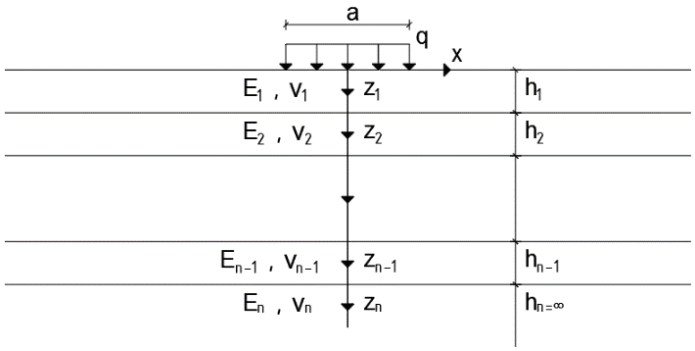


Fig. 5. Illustration of a flexible layered half-space model

Source: own work.

Analytical solutions for a homogeneous and layered half-space are known and described in the literature on the subject for both cases of static and dynamic load (Boussinesq, 1885; Burmister, 1945; Lamb, 1997; Lin, Zhang, Liu & Wang, 2016). However, from the applied side, the analytical models are very simplified. They do not make it possible to take into account physical factors that can significantly affect the measured values of displacements, e.g. imperfect layer adhesion, material anisotropy, temperature gradient, non-linearity in the behaviour of the subgrade.

In this article, the pavement model was described numerically using the finite element method. It allows for advanced deformation analysis. However, the main aim of the study is to present and evaluate methods of identifying model parameters with the use of artificial neural networks. The aim is not to precisely reproduce the structure of the layered pavement, so the FEM model was limited to an elastic isotropic domain in a plane strain state. It was also assumed that only Young's modulus would be identified due to the significant impact on deformation. Other important mechanical parameters, e.g. Poisson's ratios and thicknesses for all layers, will be known, e.g. based on structural design.

Figure 6 shows a diagram of the considered model. The model's layers correspond to the structure of the actual airport pavement (Nita, 2008). Therefore, the model consists of three structural concrete layers from the top, each with different stiffnesses. The fourth layer is natural soil. The extract of the data for the model is summarised in Table 1.

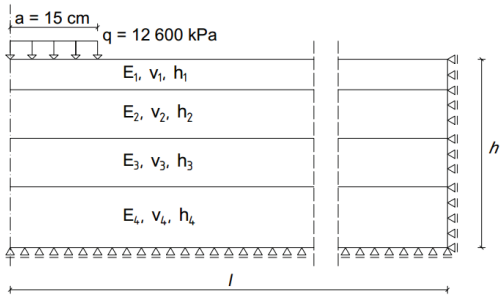


Fig. 6. Diagram of the considered layered pavement

Source: own work.

Table 1. Summary of data for the applied model of the layered pavement

Layer	h_j [cm]	ν_j [-]	E_j [GPa]
L1	20	0.2	15.0–45.0
L2	20	0.2	12.5–37.5
L3	15	0.2	7.5–22.5
L4	145	0.3	0.025–0.075

Source: own work.

Due to the symmetry of the pavement model, only half of the geometry model was considered. The dimensions of the analysed area are $l \times h = 5 \times 2$ m. A static constant load was assumed on the top surface with a width of 30 cm and a value of 12,600 kPa. The value and range of the load correspond to the static vertical contact stresses apparent under the wheel of the Boeing 747-300 airplane (Wikipedia, 2023). As boundary

condition horizontal displacements are blocked on the axis of symmetry and on the right edge of the model, a full displacement lock is used at the bottom of the model.

Figure 7 shows the finite element mesh adopted for the analysed boundary problem. Six-node triangular elements were used. The edge size of an equilateral triangle is 5 cm at the top surface of the model, evenly increasing to 15 cm at the bottom surface. The FEM model and the calculations described below were performed using the *fempy* software (Wojciechowski, 2018).

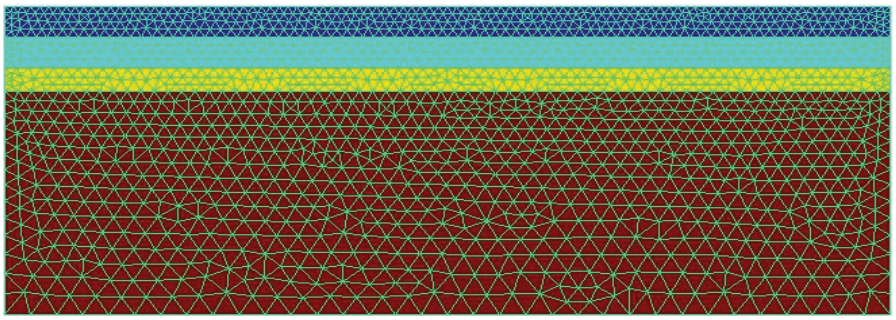


Fig. 7. Finite element mesh of the model

Source: own work.

Generation of data for ANN training

For the model defined above, 100 sets of deformation modules E_j for the four layers were randomly generated. It was assumed that all other parameters of the model are invariant. The sampling was carried out using the Latin hypercube sampling (LHS) method, which is a statistical method of generating samples with a multivariate distribution (Mckay, Beckman & Conover, 2000). It ensures that the set of samples is representative of the given ranges of parameter variability (while the usual random sampling is just a collection of random numbers with no guarantees whatsoever). Then, calculations were performed for all the generated samples, registering u_k deflections of the top surface at nine points 0, 30, 60, 90, 120, 150, 180, 210 and 240 cm from the axis of symmetry. In this way, data was obtained in sequence $(E_j^{(p)}, u_k^{(p)})$, where $E_j^{(p)}$ – elasticity modules of the layers, $u_k^{(p)}$ – deflections of the top surface, $p = 1, ..., 100$; $j = 1, ..., 4$; $k = 1, ..., 9$. Selected calculation results are presented in Figures 8–10.

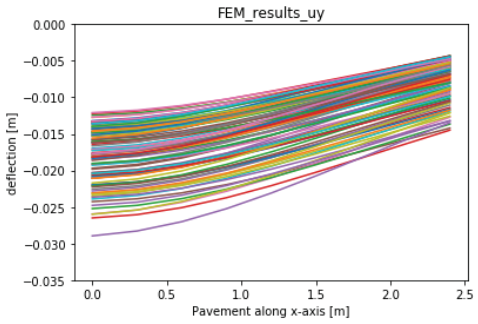


Fig. 8. Deflections of the pavement recorded in reading points for 100 random sets of E_j modules of the layers

Source: own work.

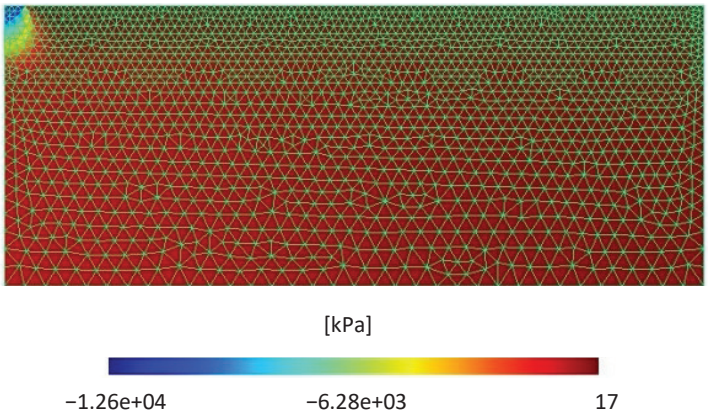


Fig. 9. Vertical stresses for the selected set of modules

Source: own work.

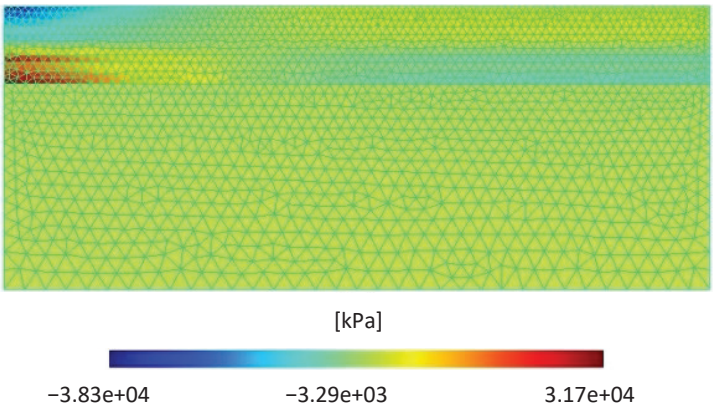


Fig. 10. Horizontal stresses for the selected set of modules. In the area of the concrete pavement, the stress distribution characteristic for the slab resting on the elastic subgrade is visible

Source: own work.

IDENTIFICATION OF MODEL PARAMETERS USING ANN

Training of artificial neural network

The fast feed-forward artificial neural network is a universal approximator of multivalued functions of several variables (Burczyński, Beluch, Długosz, Orantek & Nowakowski, 2000; Burczynski, Beluch, Długosz, Orantek & Skrobol, 2006). If the input and output of the network is interpreted as an argument and image of a certain operator or function that the ANN approximates, respectively, the consistency of the output values with the expected values should be satisfied for an infinite number of all possible sets of arguments. To achieve this, the network parameters (weights) are selected by procedure of successive corrections in an iterative process called training or teaching the network. The training of the network minimises the difference between the ANN output signal and the target signal expected at the ANN output. A popular technique that can be

found in the literature is the minimisation of the sum of squared errors calculated for all output neurons and for all input patterns, and such a formulation was used in this article. The ANN weight optimisation procedure gives the desired effect when there is a clear correlation between the input and output data. At the same time, the ANN must be designed with an appropriate number of hidden neurons, adjusted to the complexity of the objective function being approximated and to the size of the training set. Having data from the FEM model evaluation for random parameter sets, i.e. having ($E_j^{(p)}$, $u_k^{(p)}$) pairs, it is possible to train a feed-forward artificial neural network both in order to approximate the inverse relations (deflections – modules) and direct relations (modules – deflections). In this article, the *ffnet* software (Wojciechowski, 2016) was used for this purpose, which enables ANN training with the use of advanced optimisation tools, with automatic selection of the number of epochs, learning parameters and criteria for the completion of the weight selection process. In this paper, sigmoidal functions were used in the neural network models, both in the hidden layers and in the output layer. Despite the possibility of using other activation functions, this function was deliberately chosen. The *ffnet* program makes it possible to use higher-order derivatives for calculations, which is guaranteed by the sigmoid function. For example, the ReLU function does not have a second-order derivative. For all examples in the paper, the root mean squared error (RMSE) cost function was used. The cost function characterises the effectiveness of the model on the training dataset. Loss functions express the discrepancy between the predictions of the trained model and the actual occurrences of the problem. If the deviation between the predicted and actual results is too large, then the loss function will have a very high value. To accelerate the training of the network, supporting algorithms – optimisation functions – are also used. Optimisers are algorithms or methods used to change neural network attributes, such as weights and learning speed, to reduce losses. Gradient descent is the simplest but most commonly used optimisation algorithm. In this paper, the gradient descent optimiser was used.

ANN as direct approximator of the inverse relation

Method description

In this approach, an artificial neural network is defined and trained, directly mapping the inverse relationship between surface deflections and stiffness modules, which can be written as follows:

$$\tilde{E}_j = N_j^{-1}\left(u_k, \vec{w}\right), \tag{3}$$

where:
$\tilde{E}_j$ – network output, i.e. approximated elastic modules,
N_j^{-1} – operator performed by ANN,
u_k – network input in the form of pavement deflections,
$\vec{w}$ – network weights.

The trained ANN, therefore, has nine input neurons and four output neurons. The network architecture also consists of 10 hidden neurons in one layer. Network training was carried out on 95 sets of training data (training and validation sets), and the remaining five were used for network testing (test set). An example of the input and output data are presented in Table 2. The training therefore consisted in solving the following minimisation problem:

$$\min_{\vec{w}}\left[\sum_{p=1}^{95}\sum_{j=1}^{4}\left(N_j^{-1}\left(u_k^{(p)}, \vec{w}\right) - E_j^{(p)}\right)^2\right]. \tag{4}$$

Table 2. Example of inputs and outputs data for trained 9-10-4 ANN

Dataset	Input [cm]									Output [GPa]			
	D0	D30	D60	D90	D120	D150	D180	D210	D240	E_1	E_2	E_3	E_4
Training	2.15	2.12	2.03	1.92	1.78	1.63	1.47	1.30	1.14	33.75	29.48	19.10	0.03
	1.42	1.3	1.29	1.18	1.05	0.91	0.76	0.62	0.49	19.98	31.91	15.32	0.07
Testing	1.37	1.32	1.23	1.12	0.99	0.85	0.71	0.57	0.44	16.75	26.86	17.28	0.07

Note: D0, D30, etc. denotes the deflection at the geophone at 0 mm, 30 mm, etc. from the load centreline.

Source: own work.

After training the network, the identified values of the layer modules are obtained directly from the relation (3) by entering the values of the measured (test) deflection d_k on the surface. Thus, the module-matching procedure described by the formula (2) is not performed. The advantage of this approach is the very fast parameter identification process. However, their optimality, depending only on the quality of the learning process (4), is not guaranteed. Usually, however, it is possible to obtain parameters close to optimal, with an accuracy sufficient for engineering applications.

Learning and identification results

The network with the 9-10-4 architecture was trained as described above for 95 training samples. Figures 11 and 12 show the convergence results of the pattern modules and modules determined by the trained ANN for all 100 samples. The best fit is observed for the last layer – the subgrade (bottom right graph in Figure 11). Slightly poorer results are obtained for the remaining layers. It is worth noting that the fit of the test results does not deviate from the fit of the training data, which indicates that the ANN has been trained properly.

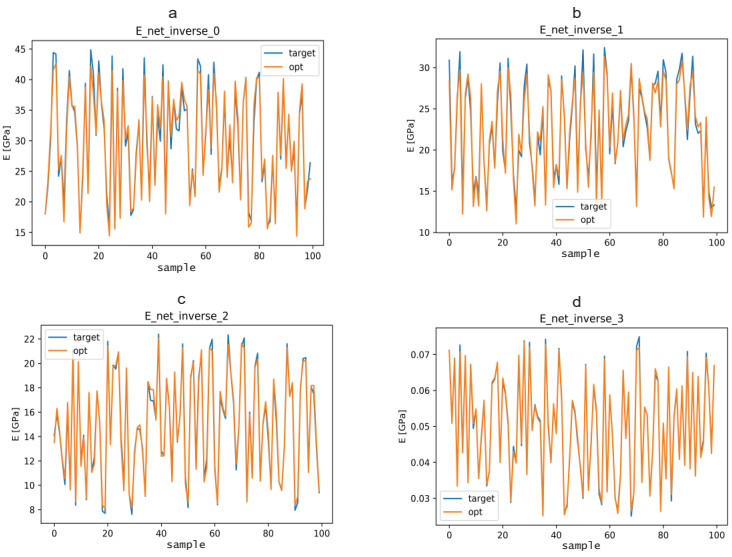


Fig. 11. Results of training the 'inverse' network N_j^{-1}: (a) 1st layer, (b) 2nd layer, (c) 3rd layer, (d) 4th layer: target – reference values of modules, opt – module values identified by the trained ANN. The last five points of the graphs refer to the testing data

Source: own work.

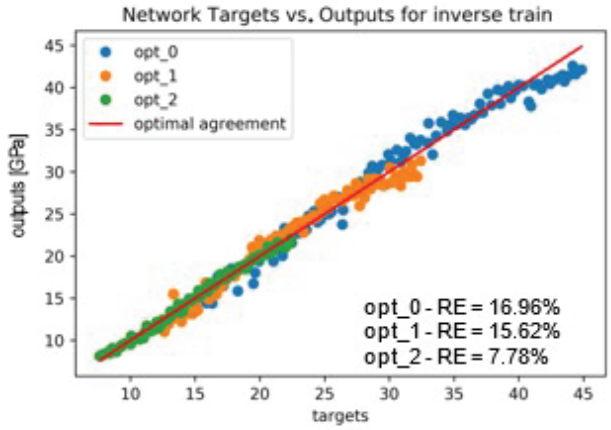


Fig. 12. Response of the 'inverse' network versus reference of the modules: E_1 (opt_0), E_2 (opt_1) and E_3 (opt_2). The points on the graph also contain test data

Source: own work.

Table 3 summarises the numerical identification results for the test samples. The average values of the modules for the model layers are also given. The differences in the computed and pattern modules do not exceed 15%, and the differences in the mean values do not exceed 5%. This indicates the ability of the network to correctly reproduce the averaged, effective properties of the layered pavement, even if the modules of the individual layers are determined with significant errors.

Table 3. Numerical compilation of the reference (target) and modules of successive layers of the model determined by the ANN (opt) for five test samples

Test	Young's moduli [GPa]	E_1	E_2	E_3	E_4	Arithmetic mean	Harmonic mean	Weighted arithmetic mean	Weighted harmonic mean
1	opt	23.75889	15.49612	9.50824	0.06691	12.20754	0.26389	4.68713	0.09213
	target	26.37433	13.31490	9.39255	0.06586	12.28691	0.25970	4.72112	0.09069
2	opt	23.32254	11.91731	13.42858	0.04248	12.17773	0.16849	4.56193	0.05854
	target	21.91036	12.93881	13.07886	0.04399	11.99300	0.17443	4.49772	0.06061
3	opt	18.87684	14.21434	18.17562	0.06081	12.83190	0.24065	4.71638	0.08377
	target	19.01810	15.04311	17.49291	0.06060	12.90368	0.23986	4.76203	0.08348
4	opt	39.26647	23.98959	18.17301	0.06916	20.37456	0.27432	7.73872	0.09529
	target	37.61994	22.84971	18.06242	0.07037	19.65061	0.27902	7.45266	0.09696
5	opt	34.83376	11.86434	11.06079	0.04532	14.45105	0.17961	5.53222	0.06243
	target	34.45835	12.87345	11.56119	0.04626	14.73481	0.18338	5.63380	0.06373

Source: own work.

In addition, the identified (opt) modules listed in Table 3 were used to perform calculations using the FEM model. The results are shown in Figure 13. The alignment of the reference (target) and identified (opt) deflections is qualitatively very good, with slight differences visible quantitatively, e.g. for Samples 2 and 5.

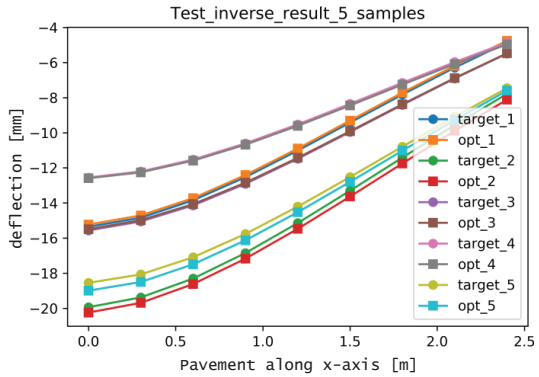


Fig. 13. Reference (target) and ANN identified (opt) deflections of the pavement for five test specimens

Source: own work.

ANN as an approximator of the model response

Method description

This approach defines and trains an artificial neural network, mapping the relationship between the layer modules and pavement deflections. In other words, the ANN directly approximates the response of the FEM numerical model to the load for given material properties. It can be written as follows:

$$\tilde{u}_k = N_k\left(E_j, \vec{w}\right), \tag{5}$$

where:

$\tilde{u}_k$ – network output, i.e. approximate pavement deflections,
N_k – operator performed by ANN,
E_j – network input in the form of layer modules,
$\vec{w}$ – net weight.

The trained ANN has four input and nine output neurons. The network architecture also consists of 10 hidden neurons in one layer. Network training was carried out on 95 training datasets (training and validation sets); the remaining five were used for network testing (test set). An example of the input and output data is presented in Table 4.

Table 4. Example of inputs and outputs data for trained 4-10-9 ANN

Dataset	Input [cm]				Output [GPa]								
	E_1	E_2	E_3	E_4	D0	D30	D60	D90	D120	D150	D180	D210	D240
Training	41.61	27.98	7.55	0.06	1.45	1.41	1.33	1.22	1.09	0.95	0.80	0.66	0.53
	17.91	29.52	15.22	0.04	2.12	2.06	1.96	1.82	1.65	1.46	1.27	1.08	8.96
Testing	39.81	27.51	9.45	0.04	2.00	1.96	1.87	1.75	1.59	1.43	1.25	1.08	0.91

Note: D0, D30, etc. denote the deflection at the geophone at 0 mm, 30 mm, etc. from the load centreline.

Source: own work.

The training, therefore, consisted of solving the following minimisation problem:

$$\min_{\vec{w}} \left[\sum_{p=1}^{95} \sum_{k=1}^{9} \left(N_k \left(E_j^{(p)}, \vec{w} \right) - u_k^{(p)} \right)^2 \right]. \tag{6}$$

After training the ANN, parameter identification consists of solving problem (2), in which the model response u_k is replaced with an approximated ANN response, i.e. the problem is solved:

$$\min_{\vec{w}} \left[\sum_{k=1}^{9} \left(N_k \left(E_j \right) - d_k \right)^2 \right]. \tag{7}$$

Another advantage of this approach is the quick identification of parameters, because calling the ANN during optimisation is many times faster than calculating the FEM model. Moreover, the determined values of the modules certainly meet the optimality criterion defined by (7). Nevertheless, as understood in the original formulation (2), the solution's optimality is still only 'approximated'. An additional advantage of the approach is the ability to easily verify whether the problem (7) has one or more solutions. From this, one can conclude the uniqueness (or lack thereof) of the inverse problem.

Learning and identification results

The network training of the 4-10-9 architecture was performed as described above for 95 training samples. Figures 14 and 15 show the results of the pattern fits and deflections determined by the trained ANN for all 100 samples. The training results are very good; significantly better than in the case of the inverse relation approximation. A perfect match of the deflection values was achieved even though ANNs with an unfavourable architecture were trained (more outputs than inputs). It is worth noting that the quality of the fit of the test results does not differ from that of the training data, which indicates that the ANN has been trained correctly.

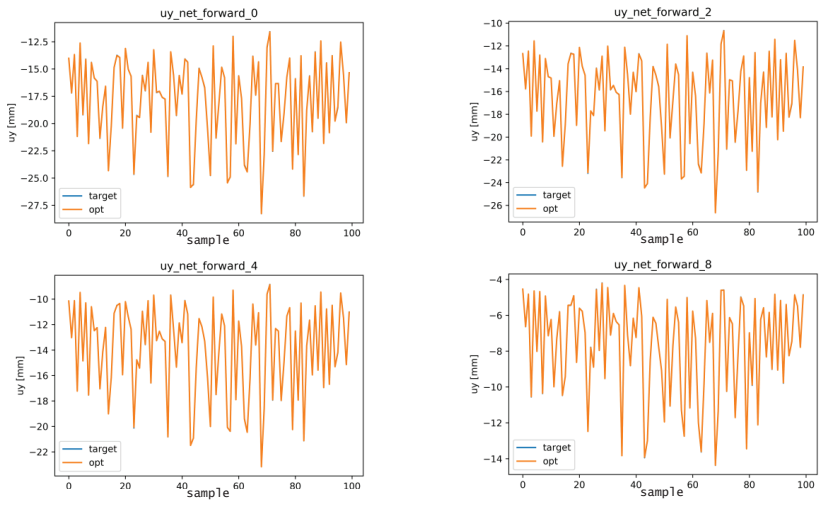


Fig. 14. Direct N_k network learning results for the 1st, 3rd, 5th and 9th reading point of pavement deflection: target – reference deflection values, opt – deflection values identified by the trained ANN. The last five points of the graphs refer to the testing data

Source: own work.

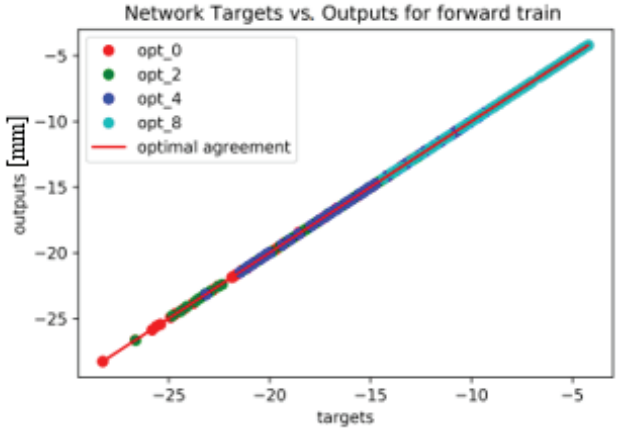


Fig. 15. Direct response of the network versus the pattern deflection values: u_1 (opt_0), u_3 (opt_2), u_5 (opt_4) and u_9 (opt_8). The points on the graph also contain test data

Source: own work.

After the ANN has been trained, the module parameters are identified by solving relation (2), in which the model response is replaced by the approximated ANN response. Therefore, the optimisation procedure (7) was used for the five test sets of deflections to identify the layer modules. This minimisation was done using the 'minimise' function from the Python language library scipy.optimize. Table 5 presents the numerical results of this identification and the averaged values of the modules. The differences in the determined and model modules are significant and may exceed even 40% in the case of concrete pavement layers, while the differences in the harmonic mean values are not greater than 5% (slightly larger differences are observed in the arithmetic means). This indicates the correct identification of the averaged, effective properties of the layered substrate, even if the modules of individual layers are determined with very significant errors in relation to the expected values.

Table 5. Numerical compilation of the reference (target) and the modules of successive layers of the model determined by optimisation defined by Formula (7) (opt) for five test samples

Test	Young's moduli [GPa]	E_1	E_2	E_3	E_4	Arithmetic mean	Harmonic mean	Weighted arithmetic mean	Weighted harmonic mean
1	opt	18.58321	18.33018	12.04275	0.06590	12.25551	0.26032	4.64233	0.09076
	target	26.37433	13.31490	9.39255	0.06586	12.28691	0.25970	4.72112	0.09069
2	opt	26.84213	21.27434	8.67345	0.04417	14.20852	0.17512	5.49418	0.06085
	target	21.91036	12.93881	13.07886	0.04399	11.99300	0.17443	4.49772	0.06061
3	opt	27.80757	21.70412	10.58812	0.06081	15.04016	0.24064	5.78936	0.08376
	target	19.01810	15.04311	17.49291	0.06060	12.90368	0.23986	4.76203	0.08348
4	opt	32.68377	23.56009	20.43075	0.07038	19.18625	0.27912	7.20772	0.09697
	target	37.61994	22.84971	18.06242	0.07037	19.65061	0.27902	7.45266	0.09696
5	opt	28.07469	21.76108	11.15155	0.04644	15.25844	0.18429	5.85362	0.06399
	target	34.45835	12.87345	11.56119	0.04626	14.73481	0.18338	5.63380	0.06373

Source: own work.

In addition, the identified (opt) modules listed in Table 5 were used to perform calculations using the FEM model to verify the fit of the reference (target) and identified pavement deflections. The results are shown in Figure 16. The alignment of the deflection lines is ideal for all test samples, despite significant discrepancies between the identified (opt) and reference (target) modules. This fact indicates the ambiguity of the considered inverse task, i.e. for different sets of modules, indistinguishable lines of pavement deflections are obtained from the FEM model.

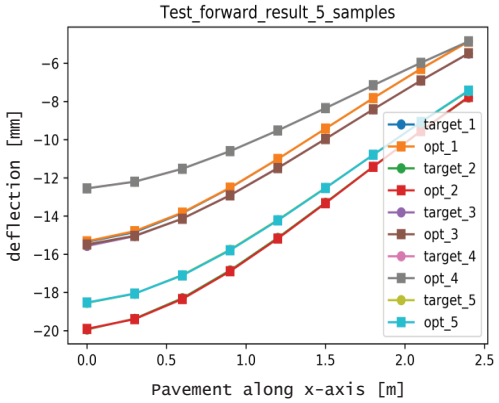


Fig. 16. Reference (target) and ANN identified (opt) deflections of the pavement for five test specimens

Source: own work.

DISCUSSION OF RESULTS AND CONCLUSIONS

The performed calculations of the identification of the parameters of the numerical model of the multi-layer pavement indicate that artificial neural networks can be successfully used for this purpose. A trained inverse network N^{-1} identifies layer modules directly, generating results with relative error not exceeding 15% (Method 1). The identification procedure using an artificial neural network N approximating the model, on the other hand, generates discrepancies in the identified modules up to 65% (Method 2). The percentages quoted only relate to rigid concrete pavement layers. In the case of the last, relatively soft layer of the subsoil, the identification results are much better; the discrepancies usually do not exceed 1% for both methods. Both methods also generate very good results in identifying the averaged, effective modules for the layers. With the mean harmonics, the divergences do not exceed 5% (see Tables 3 and 5).

The large module identification errors generated by Method 2 require a broader comment. As this method guarantees a very good adjustment of pavement deflections during the identification process, which is shown in Figure 16, obtaining very divergent modules of layers is somewhat surprising. The analysis of the variability of the minimised function while solving the problem (7) shows, however, that the solved problem of matching pavement deflections does indeed have many solutions, i.e. there are many sets of concrete pavement layer modules that generate indistinguishably close deflection lines. It is also an important observation from the point of view of Method 1, where significant network learning errors are observed (Figs 11 and 12) along with errors in deflection identification (Fig. 13). These errors are precisely the result of the reverse mapping ambiguity.

As a potential source of the ambiguity described above, we can point to the accepted ranges of variability of pavement layer modules, whose ranges partially overlap. In this context, it is worth noting the very good results of identification for the subsoil layer module, which differs from the pavement layer modules

by three orders of magnitude. The reason for the ambiguity of the inverse relation may also be the assumptions related to the FEM numerical model used (adopted boundary conditions, plane deformation state) and insufficient representation of the model response (vertical deflections on the surface at several points). This issue requires further research, especially since the problems related to the unequivocal identification of material parameters of layered pavements are also reported by other authors, including in the case of identification based on the results of actual dynamic FWD tests. One of the possible approaches for obtaining better identification results is using the sophisticated ANN learning algorithms, which can include information about the derivatives of the pavement deflection line (Wojciechowski, 2011; Wojciechowski, 2012; Raissi, Perdikaris & Karniadakis, 2017).

An important conclusion resulting from the performed calculations is that a relatively small training dataset and small neural networks are sufficient to approximate both direct and inverse relations for the FWD test. The results of training and testing of the neural networks indicate that the method of drawing training data (LHS method), the applied sizes of the neural networks and the training methods are correct. Nevertheless, further testing of the presented methods is necessary, in particular using in situ test data.

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REFERENCES

Alwattar, T. A. & Mian, A. (2019). Development of an Elastic Material Model for BCC Lattice Cell Structures Using Finite Element Analysis and Neural Networks Approaches. *Journal of Composites Science*, *3* (2), 33. https://doi.org/10.3390/jcs3020033

Aubdulnibe, F. F. & Jassim, k. A. (2019). An Application of Artificial Neural Networks (ANNs) To the Backcalculation of Flexible Pavement Moduli. *Journal of Physics: Conference Series*, *1362* (1), 012146. https://doi.org/10.1088/1742-6596/1362/1/012146

Boso, D. P. & Lefik, M. (2012). Inverse problem – Soft solution. In *Bytes and Science*. Barcelona: CIMNE.

Boso, D. P., Lefik, M. & Schrefler, B. (2012). Multiscale numerical modeling of composite material: A combined FE-ANN approach. *ECCOMAS 2012 – European Congress on Computational Methods in Applied Sciences and Engineering, e-Book Full Papers*, 8912–8926.

Boussinesq, J. (1885). *Application des potentiels à l'étude de l'équilibre et du mouvement des solides élastiques: Principalement au calcul des déformations et des pressions que produisent, dans ces solides, des efforts quelconques exercés sur une petite partie de leur surface ou de leur intérieur: Mémoire suivi de notes étendues sur divers points de physique, mathematique et d'analyse*. Paris: Gauthier-Villars.

Bredenhann, S. & Ven, M. (2004, 12 September). *Application of artificial neural networks in the back-calculation of flexible pavement layer moduli from deflection measurements*. Presented at the 8th Conference on Asphalt Pavements for Southern Africa.

Burczyński, T., Beluch, W., Długosz, A., Orantek, P. & Nowakowski, M. (2000). Evolutionary methods in inverse problems of engineering mechanics. In *Inverse Problems in Engineering Mechanics II International Symposium on Inverse Problems in Engineering Mechanics 2000 (ISIP 2000) Nagano, Japan* (553–562). https://doi.org/10.1016/B978-008043693-7/50131-8

Burczyński, T., Beluch, W., Długosz, A., Orantek, P. & Skrobol, A. (2006). Intelligent computing in inverse problem. *Computer Assisted Mechanics and Engineering Sciences*, *13* (1), 161–206.

Burmister, D. M. (1945). The General Theory of Stresses and Displacements in Layered Soil Systems. III. *Journal of Applied Physics*, *16* (5), 296–302. https://doi.org/10.1063/1.1707590

Elbagalati, O., Elseifi, M., Gaspard, K. & Zhang, Z. (2017). Development of an artificial neural network model to predict subgrade resilient modulus from continuous deflection measurements. *Canadian Journal of Civil Engineering*, *44* (9), 700–706. https://doi.org/10.1139/cjce-2017-0132

Galbusera, F., Casaroli, G. & Bassani, T. (2019). Artificial intelligence and machine learning in spine research. *JOR SPINE*, *2* (1), e1044. https://doi.org/10.1002/jsp2.1044

Gawin, D., Lefik, M. & Schrefler, B. A. (2001). ANN approach to sorption hysteresis within a coupled hygro-thermo--mechanical FE analysis. *International Journal for Numerical Methods in Engineering*, *50* (2), 299–323. https://doi.org/10.1002/1097-0207(20010120)50:2<299::AID-NME20>3.0.CO;2-Y

Lamb, H. (1997). I. On the propagation of tremors over the surface of an elastic solid. *Philosophical Transactions of the Royal Society of London. Series A, Containing Papers of a Mathematical or Physical Character*, *203* (359–371), 1–42. https://doi.org/10.1098/rsta.1904.0013

Lefik, M. & Boso, D. P. (2016). *Identification of parameters of adsorption by ap-proximation of inverse relation and using artificial neural networks*. Presented at the Proceedings Solmech2016 Conference. Retrieved from: http://www.solmech2016.ippt.pan.pl/Abstracts/0177.pdf [accessed: 14.06.2023].

Lefik, M. (2004). Hybrid, finite element-artificial neural network model for composite materials. *Journal of Theoretical and Applied Mechanics*, *42* (3), 539–563.

Li, M. & Wang, H. (2017). Development of ANN-GA program for backcalculation of pavement moduli under FWD testing with viscoelastic and nonlinear parameters. *International Journal of Pavement Engineering*, *20*, 490–498. https://doi.org/10.1080/10298436.2017.1309197

Li, M. & Wang, H. (2018). Prediction of Asphalt Pavement Responses from FWD Surface Deflections Using Soft Computing Methods. *Journal of Transportation Engineering*, *144*. https://doi.org/10.1061/JPEODX.0000044

Lin, G., Zhang, P., Liu, J. & Wang, W. (2016). Elastic solutions due to a time-harmonic point load in isotropic multi-layered media. *Structural Engineering and Mechanics*, *57*, 327–355. https://doi.org/10.12989/sem.2016.57.2.327

Mckay, M. D., Beckman, R. J. & Conover, W. J. (2000). A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code. *Technometrics*, *42* (1), 55–61. https://doi.org/10.1080/00401706.2000.10485979

Meier, R. W. (1995). *Backcalculation of flexible pavement moduli from falling weight deflectometer data using artificial neural networks*. Atlanta: Georgia Institute of Technology.

Minsky, M. & Papert, S. (1969). *Perceptrons; an Introduction to Computational Geometry*. Cambridge, MA: MIT Press.

Momeni, E., Nazir, R., Jahed Armaghani, D. & Maizir, H. (2015). Application of Artificial Neural Network for Predicting Shaft and Tip Resistances of Concrete Piles. *Earth Sciences Research Journal*, *19* (1), 85–93. https://doi.org/10.15446/esrj.v19n1.38712

Nita, P. (2008). *Budowa i utrzymanie nawierzchni lotniskowych*. Sulejówek: Wydawnictwa Komunikacji i Łączności.

Raissi, M., Perdikaris, P. & Karniadakis, G. E. (2017, 28 November). Physics Informed Deep Learning (Part I): Data-driven Solutions of Nonlinear Partial Differential Equations. *arXiv*, 1711.10561. https://doi.org/10.48550/arXiv.1711.10561

Ruta, P., Krawczyk, B. & Szydło, A. (2015). Identification of pavement elastic moduli by means of impact test. *Engineering Structures*, *100*, 201–211. https://doi.org/10.1016/j.engstruct.2015.05.038

Saltan, M. & Terzi, S. (2005). Comparative analysis of using artificial neural networks (ANN) and gene expression programming (GEP) in backcalculation of pavement layer thickness. *Indian Journal of Engineering and Materials Sciences*, *12* (1).

Shahin, M., Jaksa, M. & Maier, H. (2001). Artificial Neural Network Applications in Geotechnical Engineering. *Australian Geomechanics*, *36*, 49–62.

Shahnazari, H., Tutunchian, M., Mashayekhi, M. & Amini, A. (2012). Application of Soft Computing for Prediction of Pavement Condition Index. *Journal of Transportation Engineering*, *138* (12), 1495–1506. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000454

Tadeusiewicz, R. (1993). *Sieci neuronowe*. Warszawa: Akademicka Oficyna Wydawnicza RM.

Vahab, M., Shahbodagh, B., Haghighat, E. & Khalili, N. (2023). Application of Physics-Informed Neural Networks for forward and inverse analysis of pile–soil interaction. *International Journal of Solids and Structures*, *277–278*, 112319. https://doi.org/10.1016/j.ijsolstr.2023.112319

Wesołowski, M. & Blacha, K. (2014). Assessment of Load Capacity of the Airport Pavement Structure with the Use of the ACN-PCN Method. *Research Works of Air Force Institute of Technology*, *35* (1). https://doi.org/10.1515/afit-2015-0002

Wikipedia (2023, 12 March). *Boeing 747*. Wikipedia. Retrieved from: https://pl.wikipedia.org/w/index.php?title=Boeing_747&oldid=69845987 [accessed: 14.06.2023].

Wojciechowski, M. (2011). Application of artificial neural network in soil parameter identification for deep excavation numerical model. *Computer Assisted Mechanics and Engineering Sciences*, *18*.

Wojciechowski, M. (2012). Solving Differential Equations by Means of Feed-Forward Artificial Neural Networks. In L. Rutkowski, M. Korytkowski, R. Scherer, R. Tadeusiewicz, L. A. Zadeh & J. M. Zurada (Eds), *Artificial Intelligence and Soft Computing* (pp. 187–195). Berlin Heidelberg: Springer. https://doi.org/10.1007/978-3-642-29347-4_22

Wojciechowski, M. (2016). *ffnet: Feed-forward neural network for Python* [Python]. Retrieved from: https://github.com/mrkwjc/ffnet [accessed 15.06.2023].

Wojciechowski, M. (2018). *Fempy – Finite element method in Python* [Python]. Retrieved from: https://fempy.org/ [accessed: 15.03.2021].

Yoder, E. J. & Witczak, M. W. (1975). *Principles of Pavement Design*. Hoboken, NJ, USA: John Wiley & Sons. https://doi.org/10.1002/9780470172919

ZASTOSOWANIE METODY ELEMENTÓW SKOŃCZONYCH I SZTUCZNYCH SIECI NEURONOWYCH W IDENTYFIKACJI PARAMETRÓW NAWIERZCHNI WARSTWOWEJ

STRESZCZENIE

W artykule przeprowadzono analizę odwrotną parametrów mechanicznych istniejących nawierzchni warstwowych. Sztuczna sieć neuronowa (SSN) została wykorzystana do aproksymacji odpowiedzi modelu numerycznego nawierzchni na parametry wejściowe. Przedstawiono dwie metody. W pierwszej metodzie SSN bezpośrednio odwzorowuje odwrotną zależność między ugięciem nawierzchni a parametrami mechanicznymi. W drugiej metodzie aproksymowany model jest wykorzystywany w klasycznych obliczeniach wstecznych nawierzchni poprzez procedurę minimalizacji różnic między odpowiedzią modelu (obecnie sieci neuronowej) a pomiarami terenowymi uzyskanymi z testu ugięciomierzem dynamicznym (FWD). Identyfikowano tylko jeden parametr każdej warstwy nawierzchni – moduł Younga. Stwierdzono, że identyfikacja ta nie jest jednoznaczna. Oznacza to, że dane ugięcie można zaobserwować dla różnych zestawów modułów sztywności warstw nawierzchni. Średnia sztywność warstw jest jednak zawsze identyfikowana z dużą dokładnością.

Słowa kluczowe: sztuczna sieć neuronowa, problemy odwrotne, model numeryczny, identyfikacja parametrów, ugięciomierz dynamiczny, pomiary terenowe

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STRENGTH AND DILATANCY OF SANDS IN DIRECT SHEAR

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ABSTRACT

This article analyses the strength and dilatancy of three sands with different morphologies using four established stress–dilatancy theories. The morphology of granular materials, including sands, significantly influences their physical, mechanical, and hydraulic behaviour, mainly due to the influence of grain shape. Sands with more angular grains demonstrated higher strength and dilatancy than the ones with rounded grains. Analysing the influence of relative density and stress levels on the strength and dilatancy of sands in direct shear tests indicates that an increase in relative density enhances sand strength and dilatancy, while an increase in stress levels reduces these properties. The essential influence of grain morphology, relative density, and stress level on sand strength provides valuable insights for geotechnical applications concerning granular materials.

Keywords: sands, strength, dilatancy, direct shear

INTRODUCTION

It is important to understand the behaviour of sands under shear stress due to its direct implication on the stability of civil and geotechnical engineering structures such as slopes, embankments, retaining walls, and foundations. Granular materials such as sands tend to undergo volume changes during shearing, and this is called dilatancy (Dołżyk-Szypcio, Szypcio, Godlewski & Witowski, 2024). The complex relationship between strength and dilatancy is pivotal to understanding the factors affecting the behaviour of sands under shearing and can be described using the stress–dilatancy plane (Szypcio, 2017b; Szypcio, Dołżyk-Szypcio & Nurgaliyev, 2022a). The residual friction angle (ϕ_r) is used to describe the strength of sand under conditions of zero dilatancy, where the soil exhibits no change in volume during shearing, representing the residual shear strength in direct shear (Houlsby, 1991). Meanwhile, the factors that may affect the shearing resistance may include, but are not limited to, the inter-particle friction, distribution of particle size, particle shape, composition, surface texture, and density (Peng, Chen & Wu, 2021; Wang et al., 2021; Anusree & Latha, 2023).

The macroscopic properties of sands have been studied theoretically and in the laboratory by various researchers (Rowe, 1962; Lee & Seed, 1967; De Josselin De Jong, 1976; Scarpelli & Wood, 1982). Numerical discrete element modelling (DEM) has also been employed to study the micro-mechanical interactions and properties of sand (Wang, Dove & Gutierrez, 2007; Zhang & Thornton, 2007; Gutierrez & Wang, 2010; Amirpour Harehdasht, Hussien, Karray, Roubtsova & Chekired, 2019). It can be observed that the maximum shear strength of sand is notably influenced by the stress level and initial relative density (Dołżyk, 2006),

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and the stress–dilatancy relationship, as well as stress–strain behaviour is dependent on moisture content, normal stress, stress level and degree of compaction (Szypcio, 2017b; Dołżyk-Szypcio, 2019a). The most common theories of dilatancy proposed by Taylor (1948), Rowe (1962), Bolton (1986), Houlsby (1991), and Szypcio (2017) can correctly describe the relationship between the stress ratio and dilatancy (Dołżyk-Szypcio, 2020).

In this paper, the results of direct shear tests of three sands of different origins and grain properties published by Guida, Sebastiani, Casini and Miliziano (2019) will be analysed. The critical state frictional angle (ϕ^o) is independent of the stress level (Szypcio, 2023), but the influence of different stress levels and relative density on the strength of the sand will be analysed using four main stress–dilatancy theories (Taylor, 1948; Bolton, 1986; Houlsby, 1991; Szypcio, 2017b).

STRENGTH–DILATANCY IN DIRECT SHEAR

Following the pioneering work by Casagrande (1936), Taylor (1948) proposed a relationship between frictional angle and dilatancy. He suggested that all frictional relationships result from the internal dissipation of energy and that the dissipated energy is directly proportional to shear strain rate and normal stress. This relationship is known as the flow rule:

$$\delta W = \sigma_n' \delta\varepsilon_v + \tau\delta\gamma = (\tan\phi_r)\sigma_n'\delta\gamma \tag{1}$$

or

$$\frac{\tau}{\sigma_n'} = \left(\frac{\tau}{\sigma_n'}\right)_r + \left(\frac{\delta h}{\delta s}\right) \tag{2}$$

or

$$\tan\phi_{\text{peak}} = \tan\phi_r + \tan\psi, \tag{3}$$

where:
σ_n' – effective normal stress [kPa],
$\delta\varepsilon_v$ – volumetric strain increment [-],
τ – shear stress [kPa],
$\delta\gamma$ – shear strain increment [-],
ϕ_r – residual friction angle [°],
δh – sample height increment [mm],
δs – shear displacement increment [mm].

$$\tan\psi = \frac{-\delta\varepsilon_v}{\delta\gamma} = \frac{\delta h}{\delta s}, \tag{4}$$

where:
ψ – dilatancy angle [°].

$$\frac{\tau}{\sigma_n'} = \tan\phi_{\text{peak}}, \tag{5}$$

where:
ϕ_{peak} – peak frictional angle [°].

After analysing a series of experiments presented in the literature, Bolton (1986) proposed an empirical approach to the relationship between frictional angle and dilatancy. This empirical flow rule correlation suggests that any shear strength above the residual shear angle at a critical state is due solely to dilatancy, which occurs as a result of volume expansion and particle rearrangement:

$$\phi_{\text{peak}} = \phi_{cv} + 0.8\psi, \tag{6}$$

where:
ϕ_{cv} – critical state angle [°].

The sawtooth model proposed by Houslby (1991) considered frictional blocks sliding over another on a rough plane (sawtooth) at a dilatancy angle (ψ) to the horizontal and residual frictional angle (ϕ_r) – at constant volume or critical state – acting on the saw teeth. The relationship between shear stress and normal stress can be expressed as:

$$\frac{\tau}{\sigma_n'} = \tan\phi_{\text{peak}} = \tan\left(\phi_r + \psi\right) \tag{7}$$

or

$$\phi_{\text{peak}} = \phi_r + \psi. \tag{8}$$

Szypcio (2017b) proposed a stress–dilatancy relationship based on the frictional state concept. Equation 9 from Szypcio (2017b) correctly describes the stress–dilatancy relationship at failure in the general state (Szypcio, Dołżyk-Szypcio & Mierczyński, 2022b):

$$\tan\phi_{\text{peak}} = \frac{\tau}{\sigma_n'} = \frac{\sqrt{3}\,\eta\cos\,\phi^o\cos\theta}{3+\eta\,(\sin\theta - \sqrt{3}\sin\,\phi^o\cos\theta)}, \tag{9}$$

where:

$$\eta = \mathrm{M}_b^o - \mathrm{A}_b^o\left(\alpha + \beta D^p\right), \tag{10}$$

α, β – parameters of the frictional state concept representing the mode of deformation ($\alpha = 0$, $\beta = 1.4$),
θ – Lode angle for stress ($\theta = 15°$).

Lode angle and parameters α and β are for granular soils under plane strain (direct shear) conditions (Szypcio, 2017b).

For sands under plane strain conditions, parameters could be calculated as follows:

$$\phi^o = \phi_{cs} = \phi_r, \tag{11}$$

$$M_b^o = \frac{(3\sin\phi^o)}{\sqrt{3}\cos\theta} - \sin\phi^o\sin\theta. \tag{12}$$

For sands in drained conditions, parameters could be calculated as follows:

$$\mathrm{A}_b^o = \frac{1}{\cos\left(\theta - \theta_\varepsilon\right)}\left\{1 - \frac{2}{3}\mathrm{M}_b^o\sin\left(\theta + \frac{2}{3}\pi\right)\right\}, \tag{13}$$

$$\tan\theta_\varepsilon = \frac{1}{\sqrt{3}}\frac{\left(\frac{\delta h}{\delta s}\right)}{\sqrt{1+\left(\frac{\delta h}{\delta s}\right)^2}}, \tag{14}$$

$$D^p = \frac{\delta\varepsilon_\upsilon}{\delta\varepsilon_q} = -\sqrt{3}\frac{\left(\frac{\delta h}{\delta s}\right)}{\sqrt{1+\frac{4}{3}\left(\frac{\delta h}{\delta s}\right)^2}}, \tag{15}$$

where:

η – stress ratio [-],
$\delta\varepsilon_\upsilon$ – volumetric strain increments [-],
$\delta\varepsilon_q$ – shear strain increments [-],
D^p – plastic dilatancy [-].

CHARACTERISTICS OF ANALYSED SANDS

Guida et al. (2019) conducted a series of direct shear tests on sands of different origins and properties to study the relationship between micro-grain shape features and macro-mechanical behaviour of the sands under shearing. The sands have the same mono-disperse grain-size distribution with a grain diameter ranging between 1.0 to 1.6 mm and were prepared by dry pluviation and mechanical vibration. They were sheared in a direct shear box apparatus at a constant displacement rate of 0.18 mm·min^{-1} under three vertical stresses (σ_n equal 50, 100 and 200 kPa). Three of the sands will be analysed in this study and are selected on the basis of their morphology and geotechnical properties in order to understand the relationship between their grain shape, strength, and dilatancy. Bucarest, Fumone, and Torre del Lago sands were selected for this study. Bucarest sands are natural sands obtained from the subsurface, while Fumone and Torre del Lago sands are artificially ground and quarry-sourced, respectively.

The morphology of the sands varied significantly and reflects the geotechnical properties, shear strength, and dilatancy. Fumone sands have very angular and low sphericity grains with the highest void ratio of the three due to their irregular grains (e_{min} = 0.87, e_{max} = 1.31) and a critical state angle (ϕ_{cs}) of 37.0°. On the other hand, Torre del Lago sands comprise rounded and high sphericity grains with a void ratio of e_{min} = 0.64, e_{max} = 0.92 and the lowest shear strength with a critical state angle (ϕ_{cs}) of 26.5°. Meanwhile, Bucarest sands have sub-angular grains with high sphericity as well as a void ratio similar to Torre del Lago sands (e_{min} = 0.65, e_{max} = 0.92). In contrast, its shear strength and critical state angle (ϕ_{cs} = 30.9°) are higher than Torre del Lago sands but lower than Fumone sands. The main properties of the analysed sands are summarised in Table 1. The parameters A and α in Table 1 were calibrated against the experimental data.

Table 1. Morphological and mechanical properties of the sands

Sand name	Morphology	G_s [kg·m^{-3}]	e_{min} [-]	e_{max} [-]	ϕ_{cs} [°]	A [-]	α [-]
Bucarest	sub-angular, high sphericity	2.70	0.65	0.92	30.9	12.95	0.25
Fumone	very angular, low sphericity	2.91	0.87	1.31	37.0	15.17	0.82
Torre del Lago	rounded, high sphericity	2.70	0.64	0.92	26.7	0.31	1.01

G_s – specific gravity, e_{min} – void ratio of the soil in the densest state, e_{max} – void ratio of the soil in the loosest state, ϕ_{cs} – critical state angle, A, α – experimental parameters.

Source: Guida et al. (2019).

From Guida et al. (2019) in direct shear:

$$\psi = A D_r \left(\frac{\sigma_n}{p_a} \right)^{-\alpha}, \tag{16}$$

where:
ψ – dilatancy angle [°],
A, α – experimental parameters [-].
D_r – relative density [%],
σ_n – normal stress [kPa],
p_a – atmospheric pressure (p_a = 101) [kPa],

The dilatancy angle (ψ) is a function of the granular materials' properties (A, α), relative density (D_r), and stress level (σ_n/p_a).

INFLUENCE OF RELATIVE DENSITY ON SAND STRENGTH

The influence of relative density on the strength of Bucarest, Fumone, and Torre del Lago sands was analysed under different normal stresses (σ_n). Figures 1–3 show the relationship between ($\phi_{peak} - \phi_r$) − D_r. The results of the influence of relative density on the sand strength presented in these graphs was calculated using the equations of different stress–dilatancy theories described earlier.

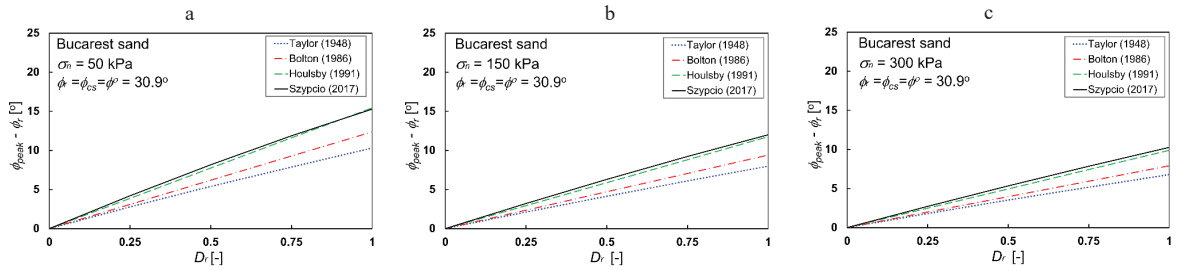


Fig. 1. The influence of relative density (D_r) on Bucarest sand strength ($\phi_{peak} - \phi_r$) for: a − σ_n = 50 kPa, b − σ_n = 150 kPa, c − σ_n = 300 kPa

Source: author's work.

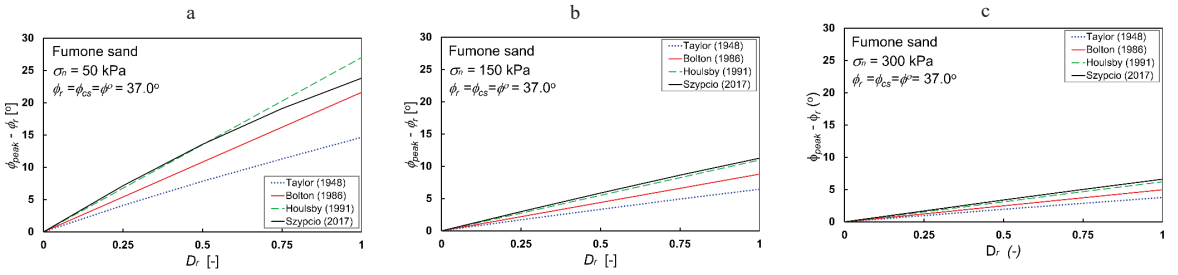


Fig. 2. The influence of relative density (D_r) on Fumone sand strength ($\phi_{peak} - \phi_r$) for: a − σ_n = 50 kPa, b − σ_n = 150 kPa, c − σ_n = 300 kPa

Source: author's work.

For Bucarest sand, an increase in relative density from 0 to 1.0 shows a progressive rise in the difference between peak and residual friction angle ($\phi_{peak} - \phi_r$). Using the Szypcio (2017b) model for $\sigma_n = 50$ kPa, $\phi_{peak} - \phi_r$ reaches approximately 15° at $D_r = 1.0$, compared to 7° at $D_r = 0.25$. A similar trend is observed for the other theories, and at higher stress levels, σ_n equals 150 kPa and 300 kPa. However, the Taylor (1948) model is least responsive to relative density, rising only to 10° at $D_r = 1.0$.

Fumone sands exhibit the most pronounced effect of relative density on sand strength (ϕ_{peak}) due to the angularity of its grains. At $\sigma_n = 50$ kPa, the Houlsby model showed that ($\phi_{peak} - \phi_r$ increases from 0 to 27° when the relative density (D_r) is increased from 0 to 1. Szypcio's (2017b) model also showed a similar increase with $\phi_{peak} - \phi_r$ rising to 25° when the relative density is 1. The Bolton (1986) model reaches 21° while the Taylor (1948) model remains the least sensitive, reaching 14.6°.

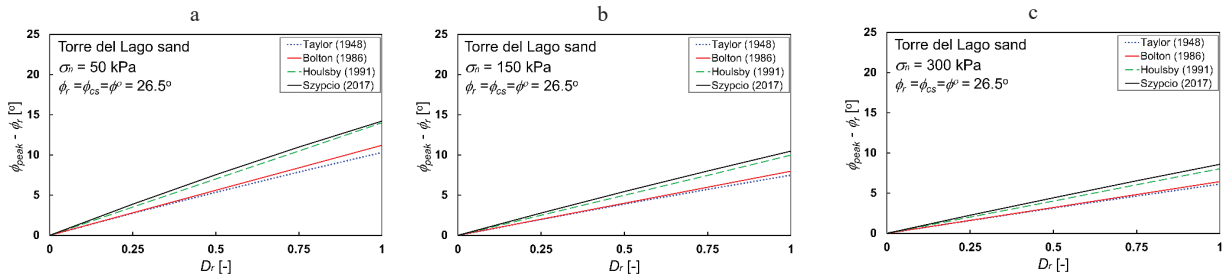


Fig. 3. The influence of relative density (D_r) on Torre del Lago sand strength ($\phi_{peak} - \phi_r$) for: a – $\sigma_n = 50$ kPa, b – $\sigma_n = 150$ kPa, c – $\sigma_n = 300$ kPa

Source: author's work.

Unlike Bucarest and Fumone, Torre del Lago sands show the least impact of relative density on sand strength due to its rounded grains that cause weaker interlocking effects and less resistance to deformation, which makes dilatancy less influential at all stress levels.

For all analysed tests, the effect of relative density on sand strength is evident with an increase in the difference between peak frictional angle and critical frictional state angle ($\phi_{peak} - \phi_r$), although the magnitude of this effect varies depending on the sand type and theoretical model. This denotes an increased sand strength and dilatancy effect in denser sands.

Taylor's (1948) model is less sensitive to relative density compared to other theories, suggesting that it may underestimate the influence of particle rearrangement and interlocking. However, Bolton (1986) shows a better effect of relative density on sand strength, especially in moderately dense sands ($D_r = 0.5$, $D_r = 0.75$). In very dense sands ($D_r = 1.0$), more detailed micromechanical theories like Houlsby (1991) and Szypcio (2017b) show a better influence on sand strength. Houlsby (1991) shows a strong influence of relative density on sand strength as it accounts for particle interlocking and geometric resistance during shearing. This is evident in angular sands like Fumone, where interlocking plays a key role in dilatancy. Frictional state theory by Szypcio (2017b), which emphasises the relationship between dilatancy and critical state theory, effectively shows the influence of relative density on sand strength. The more angular sands (Fumone) show higher sand strength, especially at $\sigma_n = 50$ kPa with $\phi_{peak} - \phi_r = 27°$; meanwhile, Bucarest and Torre del Lago sands exhibit moderate sand strength with increased relative density.

INFLUENCE OF STRESS LEVEL ON SAND STRENGTH

The effects of stress levels on the strength and dilatancy of Bucarest, Fumone, and Torre del Lago sands were analysed across various relative densities. In Figures 4–6, the relationship between the stress level and sand strength is shown for D_r of 0.25, 0.5, 0.75, and 1.0 using the four stress–dilatancy theories already discussed.

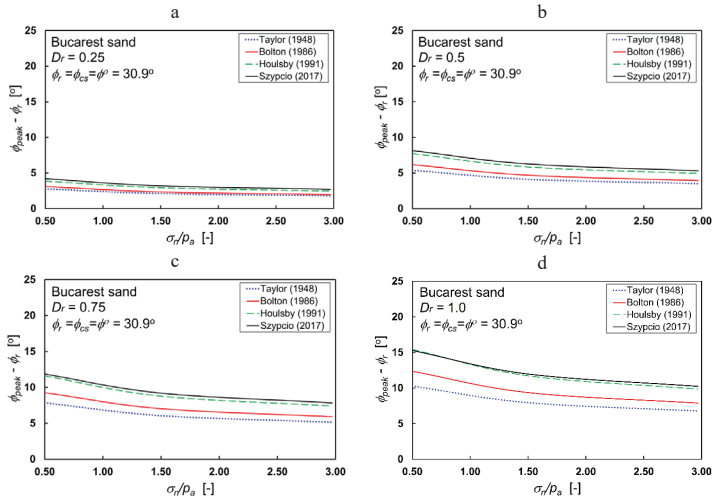


Fig. 4. The influence of stress level (σ_n/p_a) on Bucarest sand strength ($\phi_{peak} - \phi_r$) for: a – D_r = 0.25, b – D_r = 0.5, c – D_r = 0.75, d – D_r = 1.0

Source: author's work.

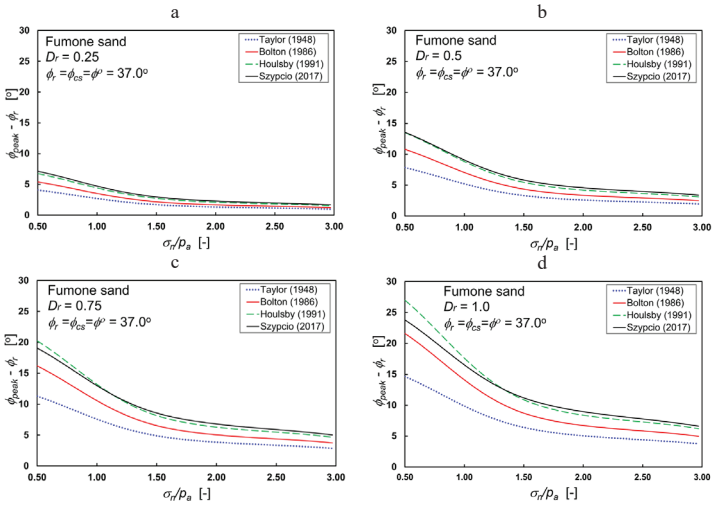


Fig. 5. The influence of stress level (σ_n/p_a) on Fumone sand strength ($\phi_{peak} - \phi_r$) for: a – D_r = 0.25, b – D_r = 0.5, c – D_r = 0.75, d – D_r = 1.0

Source: author's work.

The effect of stress level on Bucarest sand shows a gradual reduction in sand strength across all models. The Houlsby (1991) and Szypcio (2017b) models capture this decline effectively with $\phi_{peak} - \phi_r$ reducing from approximately 15° at stress level (σ_n/p_a) = 0.5°–10° at σ_n/p_a = 2.97. Taylor (1948) and Bolton (1986) also show this decline.

The effects of stress levels on Fumone sands are clearly evident, indicating that angular grains lose much of their interlocking at high normal stress. It can be observed that at lower stress levels, Fumone sands have the highest sand strength, but with an increase in stress level, there is a steeper reduction in sand strength. At D_r = 1, $\phi_{peak} - \phi_r$ reduced from 27° at σ_n/p_a = 0.5 to approximately 6° at σ_n/p_a = 2.97 using Szypcio's (2017b) model. A similar steep reduction can be observed across all models and relative densities.

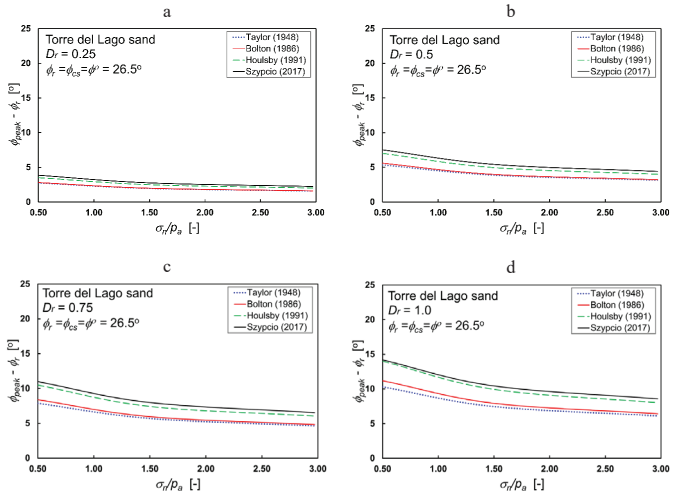


Fig. 6. The influence of stress level (σ_n/p_a) on Torre del Lago sand strength ($\phi_{peak} - \phi_r$) for: a – D_r = 0.25, b – D_r = 0.5, c – D_r = 0.75, d – D_r = 1.0

Source: author's work.

Among all the sands, Torre del Lago suffered the least noticeable reduction in sand strength when the stress level was increased. This can be attributed to its rounded grains, as an increase in stress level has only considerable effects on its interparticle friction due to reduced contributions of dilatancy. At D_r = 1, $\phi_{peak} - \phi_r$ reduces from 14.2° at σ_n/p_a = 0.5 to only about 8.5° at σ_n/p_a = 2.97, signifying a linear reduction in the strength of sand. This pattern is consistent across all densities and models.

In Figures 4–6, the influence of stress level on sand strength is characterised by a decrease in $\phi_{peak} - \phi_r$ as the stress level is increased. This denotes the reduction in sand strength and dilatancy under high normal stresses, where grain crushing may occur and particle rearrangement may be limited.

Fumone sands show the highest strength but also the steepest reduction as stress levels increase. This is due to the angular nature of the sands that makes them dilatant at low stress but become susceptible to particle breakage at higher confining stress levels, as evidently shown in Houlsby (1991) and Szypcio (2017b). Bucarest and Torre del Lago sands demonstrate lower influence on stress levels due to more rounded grains, with the latter demonstrating the least. It can also be seen from Figures 4–6 that the differences among the results from the theories of different researchers are relatively small.

Taylor (1948) underestimates the rate of strength reduction with increasing stress levels, especially in angular grain sands such as Fumone. However, Bolton (1986) captures stress dependence more effectively, showing a steeper decline in strength than the Taylor (1948) model. Szypcio's (2017b) frictional state concept and the sawtooth model by Houlsby (1991) provide a more nuanced representation, exhibiting the steepest decline in strength with an increase in stress level. Houlsby (1991) showed a sharp decrease in $\phi_{peak} - \phi_r$ at lower stress levels (σ_n/p_a = 0.5–1.5) and gradually flattens out as the stress level increases (σ_n/p_a = 1.5–3.0), indicating a reduction in dilatancy at higher confining stress levels. This model is particularly pronounced in sands with angular grains like Fumone, where grain morphology greatly affects strength. Similarly, Szypcio (2017b) shows the steepest reduction in strength with stress, reflecting a transition into critical state conditions at high stress levels where dilatancy effects are minimised and the sand approaches its residual state.

CONCLUSIONS

This study examined the influence of relative density and stress level on the strength of Bucarest, Fumone, and Torre del Lago sands. The findings revealed that the strength of sands is significantly influenced and enhanced by an increase in relative density, with a noticeable increase in the difference between $\phi_{peak} - \phi_r$ as D_r increases from 0 to 1.0. This increase was more pronounced in very angular sands like Fumone, where its morphology contributed to an increase of up to 27° at D_r = 1.0 under low stress conditions (σ_n = 50 kPa), compared to Bucarest and Torre del Lago, which exhibited increases of around 16° and 14°, respectively. Houlsby's (1991) and Szypcio's (2017b) models consistently predicted higher strength gains, emphasising the significant role of dilatancy in dense sands.

Conversely, the increase in stress level (σ_n/p_a) reduces the sand strength, particularly under high stress levels where dilatancy reduces and particle breakage occurs. It was observed that $\phi_{peak} - \phi_r$ decreased with a rise in σ_n for all sands; this reduction was steepest for very angular sands such as Fumone, where at D_r = 0.75, $\phi_{peak} - \phi_r$ reduced from 20° at 50 kPa to 5° at 300 kPa, as captured by the Houlsby (1991) and Szypcio (2017b) models. In contrast, Torre del Lago sand shows less pronounced reduction due to its rounded grains, and Bucarest sand shows moderate reductions.

For all sands, Taylor (1948) and Bolton (1986) tend to underestimate the strength changes as density and stress levels are changed. In comparison, Houlsby (1991) and Szypcio (2017b) provide better predictions of the sand strength, particularly for dense sands under varying stress conditions. Angular sands like Fumone exhibit the highest sensitivity to both density and stress level, while rounded sands like Torre del Lago show the least sensitivity and Bucarest sands display moderate strength characteristics.

Overall, the results of this study showed the complex relationship between relative density, stress level and grain morphology in determining the strength of sands. These insights are important in modelling sand behaviour in engineering and optimising designs under varying density and stress conditions.

Acknowledgements

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REFERENCES

Anusree, K. V. & Latha, G. M. (2023). Characterization of sand particle morphology: state-of-the-art. *Bulletin of Engineering Geology and the Environment*, *82* (269). https://doi.org/10.1007/s10064-023-03309-x

Amirpour Harehdasht, S., Hussien, M. N., Karray, M., Roubtsova, V. & Chekired, M. (2019). Influence of particle size and gradation on shear strength–dilation relation of granular materials. *Canadian Geotechnical Journal*, *56*, 208–227. https://doi.org/10.1139/cgj-2017-0468

Bolton, M. D. (1986). The strength and dilatancy of sands. *Géotechnique*, *36* (1), 65–78. https://doi.org/10.1680/geot.1986.36.1.65

Casagrande, A. (1936). Characteristics of cohesionless soils affecting the stability of slopes and earth fills. *Journal of the Boston Society of Civil Engineers*, *23* (1), 13–32.

De Josselin De Jong, G. (1976). Rowe's Stress-Dilatancy Relation based on friction. *Géotechnique*, *26* (3), 527–534. https://doi.org/10.1680/geot.1976.26.3.527

Dołżyk, K. (2006). The Non-Linear Mohr-Columb Model for Sands. *Studia Geotechnica et Mechanica*, *28*, 2−4.

Dołżyk-Szypcio, K. (2019). Direct shear test for coarse granular soil. *International Journal of Civil Engineering*, *17*, 1871-1878. https://doi.org/10.1007/s40999-019-00417-2

Dołżyk-Szypcio, K. (2020). Stress−Dilatancy Relationship of Erksak Sand Under Drained Triaxial Compression. *Geosciences*, *314* (10), 353. https://doi.org/10.3390/geosciences10090353

Dołżyk-Szypcio, K., Szypcio, Z., Godlewski, T. & Witowski, M. (2024). Stress–Dilatancy Behavior of Alluvial Sands. *Applied Science*, *14*, 6228. https://doi.org/10.3390/app14146228

Guida, G., Sebastiani, D., Casini, F. & Miliziano, S. (2019). Grain morphology and strength-dilatancy of sands. *Géotechnique Letters*, *9*, 1–19. https://doi.org/10.1680/jgele.18.00199

Gutierrez, M. S. & Wang, J. (2010). Discrete element simulations of direct shear specimen scale effects. *Géotechnique*, *60* (5), 395–409. https://doi.org/10.1680/geot.2010.60.5.395

Houlsby, G. T. (1991). How the dilatancy of soils affects their behaviour. *Proceedings of the Tenth European Conference on Soil Mechanics and Foundation Engineering*, *4*, 1189–1202.

Lee, K. L. & Seed, H. (1967). Drained strength characteristics of sands. *Journal of Soil Mechanics Foundations Division*, *ASCE*, *93* (6), 117–141.

Peng, Z., Chen, C. & Wu, L. (2021). Numerical Investigation of Particle Shape Effect on Sand Shear Strength. *Arabian Journal for Science and Engineering*, *46*, 10585–10595. https://doi.org/10.1007/s13369-021-05430-z

Rowe, P. W. (1962). The stress-dilatancy relation for static equilibrium of an assembly of particles in contact. *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *269* (1339), 500–527. https://doi.org/10.1098/rspa.1962.0193

Scarpelli, G. & Wood, D. M. (1982). *Experimental observations of shear band patterns in direct shear tests*. In Proceedings of *the IUTAM Conference on Deformation and Failure of Granular Materials* (pp. 472–484). Delft.

Szypcio, Z. (2017a). Stress–dilatancy for soils. Part III: Experimental validation for the biaxial condition. *Studia Geotechnica et Mechanica*, *39* (1), 73–80. https://doi.org/10.1515/sgem-2017-0007

Szypcio, Z. (2017b). Stress–dilatancy for soils. Part IV: Experimental validation for simple shear conditions. *Studia Geotechnica et Mechanica*, *39* (1), 81–88. https://doi.org/10.1515/sgem-2017-0008

Szypcio, Z. (2023). *Stress-dilatancy behaviour of calcareous sand*. In Proceedings of the *8th International Symposium on Deformation Characteristic of Geomaterials (ISDCG2023),* Porto, Portugal, 3–6 September 2023. Retrieved from: https://www.issmge.org/publications/publication/stress-dilatancy-behaviour-of-calcareous-sands [accessed: 24.04.2024].

Szypcio, Z., Dołżyk-Szypcio, K. & Nurgaliyev, A. (2022a). Stress-dilatancy relationship of sand-rubber mixtures. *IOP Conference Series: Materials Science and Engineering*, *1260*, 012003. https://doi.org/10.1088/1757-899X/1260/1/012003

Szypcio, Z., Dołżyk-Szypcio, K. & Mierczyński, J. (2022b). Dilatant nature of sand shear strength. *Applied Sciences*, *12* (5), 2332. https://doi.org/10.3390/app12052332

Taylor, D. W. (1948). *Fundamentals of soil mechanics*. New York: John Wiley and Sons.

Wang, J., Dove, J. E. & Gutierrez, M. S. (2007). Discrete-continuum analysis of shear banding in the direct shear test. *Géotechnique*, *57* (6), 513–526. https://doi.org/10.1680/geot.2007.57.6.513

Wang, T., Ma, L., Wang, M., Li, Z., Zhang, X. & Geng, H. (2021). Effects of particle shape on dynamic mechanical behaviours of coral sand under one-dimensional compression. *Engineering Geology*, *304*, 106624. https://doi.org/10.1016/j.enggeo.2022.106624

Zhang, L. & Thornton, C. (2007). A numerical examination of the direct shear test. *Géotechnique*, *57* (4), 343–354. https://doi.org/10.1680/geot.2007.57.4.343

WYTRZYMAŁOŚĆ I DYLATANCJA PIASKÓW W BEZPOŚREDNIM ŚCINANIU

STRESZCZENIE

W artykule analizowano wytrzymałość i dylatancję trzech piasków o różnej morfologii w świetle czterech wybranych teorii opisujących współzależność naprężenia i dylatancji. Morfologia materiałów ziarnistych, w tym piasków, znacząco wpływa na ich cechy fizyczne, mechaniczne i hydrauliczne, głównie ze względu na wpływ kształtu ziaren. Piaski o ziarnach bardziej ostrokrawędzistych wykazały większą wytrzymałość i dylatancję niż te o ziarnach zaokrąglonych. Analiza wpływu gęstości względnej oraz poziomów naprężeń na wytrzymałość i dylatancję piasków w badaniach bezpośredniego ścinania wskazuje, że wzrost gęstości powoduje zwiększenie wytrzymałości i dylatancji piasku, podczas gdy wzrost poziomu naprężeń powoduje ich zmniejszenie. Wpływ morfologii ziaren, gęstości względnej i poziomu naprężeń na wytrzymałość piasku dostarcza cennych spostrzeżeń dotyczących materiałów ziarnistych.

Słowa kluczowe: piaski, wytrzymałość, dylatancja, bezpośrednie ścinanie

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ORIGINAL PAPER

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A COMPARATIVE ANALYSIS OF HIGH-RISE BUILDING MODELS AS A DATA SOURCE FOR MULTIDIMENSIONAL CADASTRE

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ABSTRACT

The paper presents a problem related to the limitations of the current form of cadastre used in Poland – the two-dimensional cadastre, which is often insufficient for technological developments. The problem was presented by means of a comparative analysis of six selected high-rise buildings in Warsaw, which are characterised by complex solid geometry: Rondo 1, Skysawa, Złota 44, Central Tower, Forest and LIM Centre. The introduction discusses the limitations of the two-dimensional cadastre, as well as the opportunities presented by a multipurpose cadastre, which, thanks to integration with GIS systems and BIM technology, might be a revolution in the Polish cadastral system. In the analytical part, two models of each analysed high-rise building were created in Revit using the data available in the national Land and Building Register (EGiB) and the available data on the actual building to present the inaccuracies of the two-dimensional cadastre in more detail. The urban indicators calculated according to the Land and Building Register were also compared with the actual indicators, confirming that the cadastre in its current form is insufficient for a reliable depiction of reality.

Keywords: multidimensional cadastre, high-rise buildings, BIM

INTRODUCTION

A cadastre, according to a statement on cadastre prepared by the International Federation of Surveyors (FIG), is "usually a plot-based current land information system containing a register of interests in land (e.g. rights, restrictions and obligations). It generally contains a geometric description of the parcels linked to other records describing the nature of the interests, the ownership or control of those interests, and often the value of the parcel and its improvements." (International Federation of Surveyors [FIG], 1998). The basic cadastre can be divided into three types: fiscal, legal, and physical real estate (Etel, Dowgier, Liszewski, Poplawski & Presnarowicz, 2008). The first type is responsible for the taxation of land, the second for the protection of land rights and the development of the real estate market (Bydłosz, 2012), and the third registers maps, plans, and real estate data (Kopyściańska, 2017).

The two-dimensional cadastre has its limitations. One of them is its two-dimensional graphic representation, which does not consider height information and the spatial properties of buildings in the third dimension. Buildings and underground infrastructure are interconnected, while the solidity of buildings

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varies according to height. With two-dimensional cadastre maps, buildings start to overlap, making it impossible to obtain real information. Another limitation is the impossibility of presenting RRR (acronym for: rights, restrictions, and responsibilities) information. Within a single location, there are different forms of ownership at different elevation levels, so there is a problem of vertical overlap in the two-dimensional cadastre (Atazadeh et al., 2021).

In Poland, the main problem of the two-dimensional cadastre is that according to the Decree of the Minister of Development, Labour and Technology of 27 July 2021 on the land and buildings register, buildings are defined by the projection on the horizontal plane of the external planes of the external walls of the ground storey of a building, and in buildings founded on pillars on the basis of the projection of the external planes of the external walls of the storey resting on these pillars (Rozporządzenie Ministra Rozwoju, Pracy i Technologii z dnia 27 lipca 2021 r.). This means that the national Land and Building Register (Polish: *Ewidencja gruntów i budynków* – EGiB) does not consider the projections of the planes formed by the external walls of the upper storeys, which can vary according to height. In its current form, the cadastral system in Poland is not intended to be a universal solution governing all economic and spatial aspects (Noszczyk & Hernik, 2019). The main functions of the cadastre are tax (fiscal) and legal issues (Borkowski, Adamczyk, Gadosz, & Marynowski, 2025). The economic dimension is also important here, as it is necessary for the valuation of real estate since prices are primarily determined based on area (Baumane, 2010).

A new concept of a multipurpose cadastre is currently described in the literature. It is an elaborate system that not only records property data but also allows its analysis in the context of different domains, such as environmental protection, urban planning, transport, and disaster management (Bennett, Rajabifard, Kalantari, Wallace & Williamson, 2011). A multipurpose cadastre includes different layers of information that are processed and used for different purposes, making it a more versatile tool than a traditional cadastre (Uşak, Çağdaş & Kara, 2024). By integrating with GIS systems, a multipurpose cadastre allows the visualisation of spatial data and more precise decision-making, which is particularly important in the context of sustainable development, natural resource conservation, and urban planning (Li & Gar-On Yeh, 2000).

An even more accurate tool necessary for the implementation of a multipurpose cadastre is BIM, which has many benefits, especially if it accompanies the building from its inception (Kjartansdóttir, Mordue, Nowak, Philp & Snæbjörnsson, 2017). An additional advantage of BIM technology is the ability to integrate with GIS systems (Borkowski, Osińska & Szymańska 2022) due to BIM's focus on microrepresentations of the buildings themselves and the provision of macrorepresentations of external building environments by GIS (Wang, Pan & Luo, 2019). Digital models of buildings made with BIM or GIS can allow more accurate identification of properties in cadastral systems, among others. In addition to solving property problems, detailed information about the geometry of buildings will allow for more accurate analyses (Sun, Mi, Olsson, Paulsson & Harrie, 2019).

The lack of comprehensive studies on the integration of BIM with GIS technologies (Borkowski & To Duc 2024) to improve the quality of the cadastre in Poland currently limits the possibilities to fully exploit the potential of these technologies. There is also a paucity of analyses comparing the geometric data of buildings in the EGiB with reality and their impact on key urban planning parameters important in the context of spatial planning, such as total area or building intensity.

Thus, the aim of the study was a comparative analysis of high-rise building models developed based on the EGiB data and reality. The study aimed to identify the limitations associated with the two-dimensional cadastre, to identify the differences between the data available in the EGiB and the actual parameters of buildings, and to assess the impact of these differences on the actual urban indicators and those developed based on the data available in the EGiB.

MATERIAL AND METHODS

Figure 1 presents a methodology for conducting a comparative analysis of high-rise building models that can serve as a data source for a multidimensional cadastre. The process is divided into seven complementary steps.

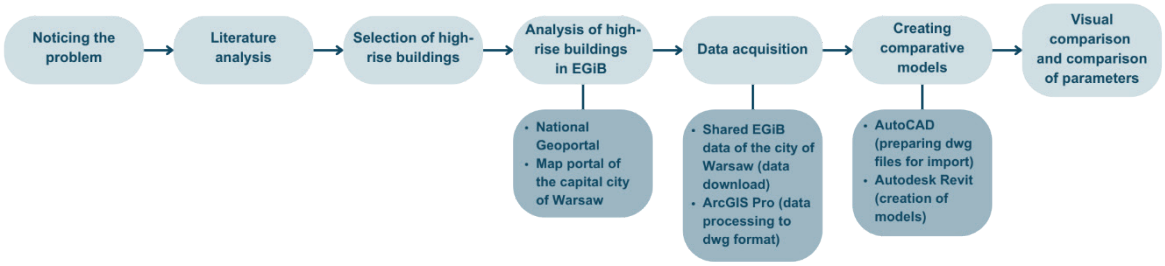


Fig. 1. Analysis of materials and methods flowchart

Source: own work.

The first step was to note the problem, which was then identified and clarified. On this basis, a literature analysis was carried out, focusing on the definition, types and functions of the cadastre, the limitations of its two-dimensional form and the concept of a multipurpose cadastre. This culminated in the identification of the research gap and the research objective. The next step was the selection of high-rise buildings, i.e. the selection of buildings to be analysed as part of the study. These buildings were then analysed in the EGiB based on information made available by the National Geoportal and the Warsaw City mapping service. Following the analysis, the EGiB data was downloaded in shp format and then processed in ArcGIS Pro into dwg format. This enabled further preparation of files in AutoCAD for import into Autodesk Revit, which then produced two versions of the building model (a building developed based on the EGiB information alone and a building mapped in accordance with the actual geometry). The final stage of the study involved comparing the two models. The analysis focused on a visual comparison and a comparison of parameters such as the built-up area, total built-up area and building intensity.

CASE STUDIES

At the selection stage, six high-rise buildings in Warsaw characterised by specific geometric building forms were selected for analysis, which, once analysed, will make it possible to demonstrate the lack of precision of the two-dimensional cadastre and to consider the possibilities associated with the multipurpose cadastre:

1. Rondo 1 – A high-rise building located at Rondo ONZ 1 in Warsaw, the construction of which was completed in March 2006 (Urbanity, 2021). The total area of this high-rise building is 103,000 m^2. It consists of two buildings – Building A, with 10 above-ground storeys and two underground storeys, and Building B, with 41 above-ground storeys and two underground storeys. The building's height to the roof is 159 m, while its structural height is 192 m. Its function is primarily focused on offices and services (Rondo 1, 2025).
2. Skysawa – A high-rise building located at Rondo ONZ (Świętokrzyska 36/34 in Warsaw), the construction of which was completed in 2022 (Skysawa, 2025). The total area of this high-rise building is 34,550 m^2. It consists of two buildings – Building A with 9 above-ground storeys and 3 underground storeys, and Building B with 40 above-ground storeys and 3 underground storeys. The height of the building is 155 m. Its function is primarily focused on offices and retail (Skysawa, 2025).

3. Złota 44 – A high-rise building located on Złota 44 in Warsaw, the construction of which was completed in 2013. It is the tallest residential development in the European Union – it is 192 m high (55 storeys) and has two underground storeys (Złota 44, 2025). The total area of this building is 77,071 m^2 (Puls Biznesu, 2022), within which there are 287 flats and 1,800 m^2 of amenity space for residents, such as a swimming pool, gym, and sauna (Złota 44, 2025).
4. Central Tower – A high-rise building located at Rondo Czterdziestolatka (Al. Jerozolimskie 81 in Warsaw), the construction of which was completed in 1996. The total area of this high-rise building is 20,804 m^2, including 14,460 m^2 of leasable area (Knight Frank, 2025). It consists of 26 floors above ground. The height of the building is 115 m. Its function is primarily focused on offices.
5. Forest – An office campus located at Rondo Zgrupowania Armii Krajowej "Radosław" (Burakowska 14 in Warsaw), the construction of which was completed in 2022 (HB Reavis, 2023). The complex consists of a 120 m high high-rise building (29 storeys) and adjacent buildings with six to eight storeys (Sarniewicz, 2022). In addition, there are three underground floors with 500 parking spaces for bicycles and 800 for cars (HB Reavis, 2023). The total area of the campus is 78,990 m^2, of which 71,000 m^2 is for office space and 5,000 m^2 for retail and service functions (Urbanity, 2025).
6. LIM Centre – A high-rise building located at Rondo Czterdziestolatka (Al. Jerozolimskie 65/79 in Warsaw), the construction of which took place in the late 1980s. (Urbanity, 2025). The total area of this high-rise building is 86,000 m^2. It consists of a three-storey podium and a tower with a total of 42 floors above ground. There are also two underground floors. The height of the building is 140 m. Its function focuses primarily on offices, retail, and hospitality (LIM Center, 2021).

RESULTS

Rondo 1

The Land and Building Register (EGiB) analysis

According to the Land Registry (Fig. 2), the built-up area of the Rondo 1 high-rise building is 4,700 m^2, and its number of above-ground floors is 10 and 40 for Building A and Building B, respectively. This high-rise building is located on two plots of land: 36/4 and 40, precinct 5-03-08. Their total area is 5,820 m^2.



Fig. 2. The Rondo 1 high-rise building in the Land and Building Register (EGiB)

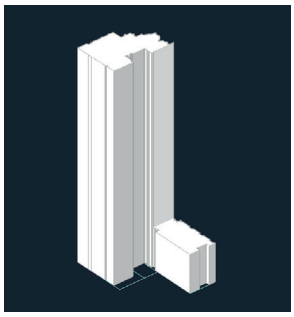
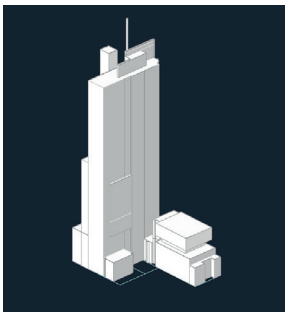
Source: Główny Urząd Geodezji i Kartografii [GUGiK] (2025).

However, there is an inconsistency in the EGiB regarding the number of storeys of Building B, as according to the information from the developer, there are 41 above-ground storeys. Information on two underground storeys is also missing.

Comparative model

The model of the high-rise building created based on the data in the EGiB does not reflect the true appearance of the high-rise building. The model has a very simplified geometry of the building with a shape like two cuboids joined together, and it does not consider more complex architectural elements that may affect the spatial representation (Table 1). This simplification means that the model does not fully represent the actual shape or proportions of the building (Table 2).

Table 1. Models of Rondo 1 made in Autodesk Revit

The building according to the Land and Building Register (EGiB)		The building in reality	
			

Source: own work.

Table 2. Differences in the parameters of the Rondo 1 models

Specification	The building according to the Land and Building Register (EGiB)	The building in reality
Building area	4,700 m^2	4,700 m^2
Total built-up area	139,535 m^2	103,000 m^2
Building intensity	24.0	17.7

Source: own work.

Due to the same building footprint, the built-up area is the same in both cases. The difference is noticeable in the total built-up area and building intensity. The building model, according to EGiB, has overestimated the parameters by 36,535 m^2 and 6.3, respectively.

Skysawa

The Land and Building Register (EGiB) analysis

According to the data contained in the EGiB (Fig. 3), the built-up area of the Skysawa high-rise building is 2,990 m^2 and its number of storeys is 38. The area of the plots on which it is located (20/1, 20/3, 20/4, precinct 5-03-06) is 5,970 m^2.



Built-up area: 2,990 m^2

Number of storeys: 38

Plot area: 5,970 m^2

Fig. 3. The Skysawa high-rise building in the Land and Building Register (EGiB)

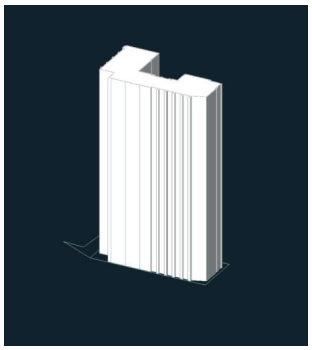
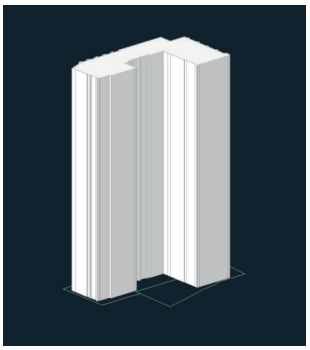
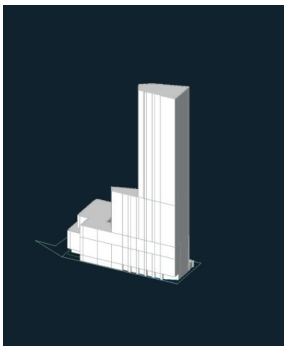
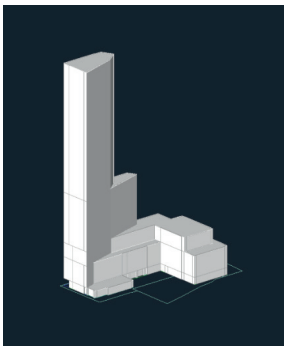
Source: GUGiK (2025).

Comparing this information to the actual state, inconsistencies in the number of storeys can be seen. The building has 40 above-ground storeys and three underground storeys, which is not reflected in the EGiB data. The register also does not consider the fact that the high-rise building consists of two buildings with a different number of storeys.

Comparative model

The model of the high-rise building created based on the data in the EGiB does not reflect the true appearance of the high-rise building. The model has a very simplified geometry of the building with a shape like two cuboids joined together, and it does not consider more complex architectural elements that may affect the spatial representation (Table 3). This simplification means that the model does not fully represent the actual shape or proportions of the building (Table 4).

Table 3. Models of Skysawa made in Autodesk Revit

The building according to the Land and Building Register (EGiB)		The building in reality	
			

Source: own work.

Table 4. Differences in the parameters of the Skysawa models

Specification	The building according to the Land and Building Register (EGiB)	The building in reality
Building area	2,990 m^2	2,990 m^2
Total built-up area	113,620 m^2	34,550 m^2
Building intensity	19.0	5.8

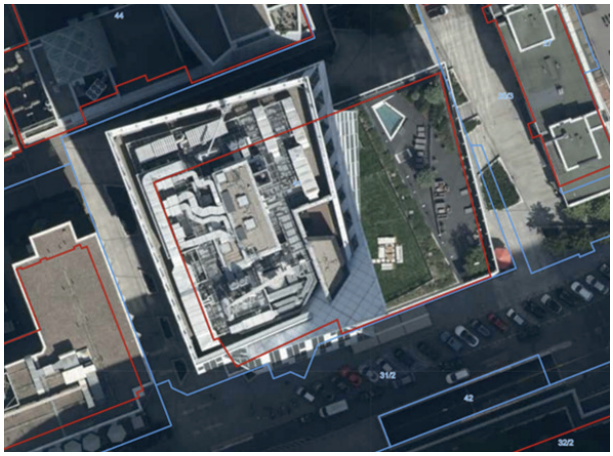
Source: own work.

Due to the same building footprint, the built-up area is the same in both cases. The difference can be seen in the total built-up area and amounts to 79,070 m^2, which directly affects the difference in building intensity of 13.2.

Złota 44

The Land and Building Register (EGiB) analysis

According to the EGiB (Fig. 4), the built-up area of the high-rise building is 2,048 m^2, and its number of storeys is 55. The area of the plot on which it is located (41, precinct 5-03-08) is 4,407 m^2.



Built-up area: 2,048 m^2

Number of storeys: 55

Plot area: 4,407 m^2

Fig. 4. The Złota 44 high-rise building in the Land and Building Register (EGiB)

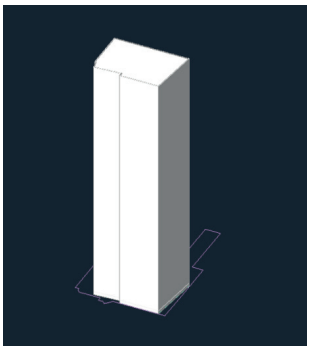
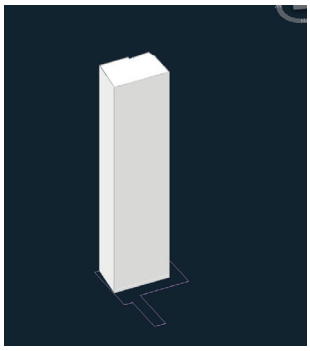
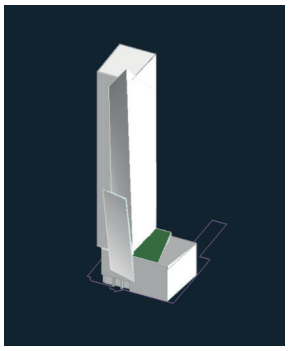
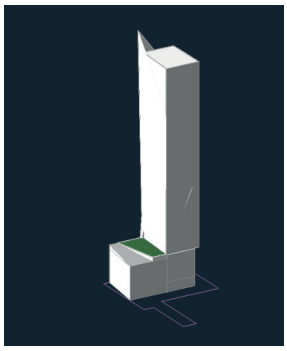
Source: GUGiK (2025).

In the case of Złota 44, the number of above-ground storeys is the same in the records. The number of underground storeys in the inventory is not included, thus there is an anomaly when compared to the actual building (Table 5). The records also do not consider the fact that only part of the building is elevated at 55 storeys.

Comparative model

The model of the high-rise building created based on data in the EGiB shows the building as a simple block. It does not consider the elements of architecture, which, thanks to technological progress, is able to take increasingly complex forms. In this case, the height part of the building first decreases in circumference and then increases to the highest point of the building. In the records, such structural changes are not recorded. At a height of approximately 30 m, the high-rise building has an overhang that extends the massing beyond the building's perimeter (Fig. 5), which may affect the lighting of the space below.

Table 5. Models of Złota 44 made in Autodesk Revit

The building according to the Land and Building Register (EGiB)		The building in reality	
			

Source: own work.



Fig. 5. Representation of the building overhang extending beyond the outline of the building at ground level

Source: Google Streetview.

It can also cause spatial or ownership conflicts if the projecting section extends beyond the plot boundary. Due to the same building footprint, the built-up area is the same in both cases. The difference can be seen in the total built-up area, which amounts to 35,569 m^2. This results in a significant increase in building intensity for the model developed according to the EGiB (Table 6).

Table 6. Differences in the parameters of the Złota 44 models

Specification	The building according to the Land and Building Register (EGiB)	The building in reality
Building area	2,048 m^2	2,048 m^2
Total built-up area	112,640 m^2	77,071 m^2
Building intensity	25.6	17.5

Source: own work.

Central Tower

The Land and Building Register (EGiB) analysis

According to the EGiB (Fig. 6), the built-up area of the Central Tower high-rise building is 645 m^2, and its number of storeys is 26. This high-rise building is located on plot 36, precinct 2-01-02, with an area of 807 m^2. The ground outline of the building also extends minimally into plot 40/2 in the same area to the north. The number of storeys provided by the developer agrees with the number of storeys in the EGiB. An understatement in the EGiB is the outline of the high-rise building due to the height at which the survey measurements for the EGiB are carried out. At a height of about 5 m, an overhang appears, and this outline changes. The outline of the high-rise building at ground level is shown in red, while the outline of the high-rise building at a height of approximately 5 m is shown in blue in Figure 7.



Built-up area: 645 m^2

Number of storeys: 26

Plot area: 807 m^2

Fig. 6. The Central Tower high-rise building in the Land and Building Register (EGiB)

Source: GUGiK (2025).

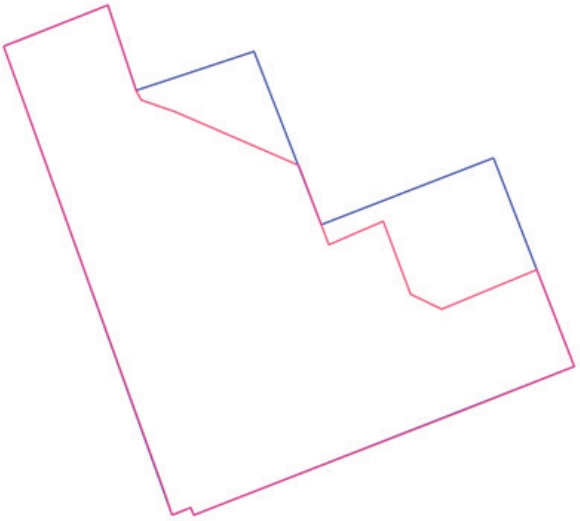


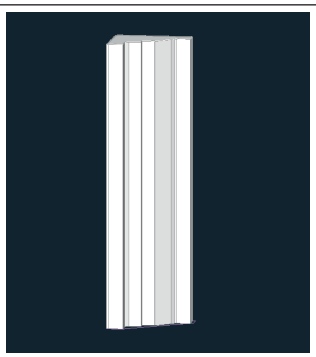
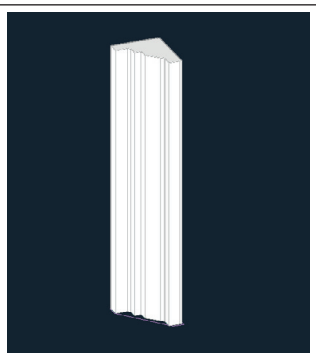
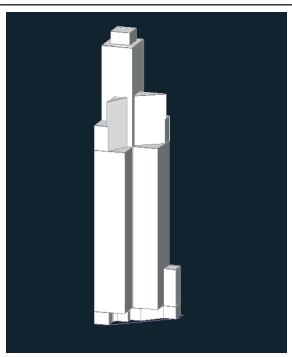
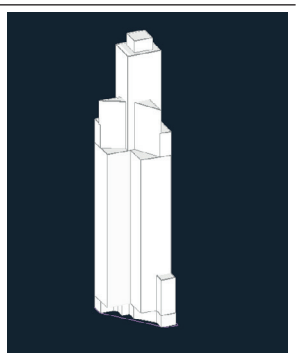
Fig. 7. A comparison of the high-rise building's outline at ground level and the outline at a height of about 5 m

Source: own work based on a building outline from the Land and Building Register (EGiB) and a digital surface model (GUGiK, 2025).

Comparative model

The high-rise building model created based on the EGiB has a very simplified geometry and differs significantly from the actual form (Table 7). The biggest difference that can be noticed first is that there are walls that extend beyond the outline of the high-rise building in the EGiB. In addition, the model created based on the EGiB lacks characteristic features, as the model of the high-rise building reproducing the actual shape of the building contains additional massing and features that faithfully reproduce the characteristic architectural features of the building, including irregularities in the shape of the façade and level differences on the roof (Table 8).

Table 7. Models of Central Tower made in Autodesk Revit

The building according to the Land and Building Register (EGiB)		The building in reality	
			

Source: own work.

Table 8. Differences in the parameters of the Central Tower models

Specification	The building according to the Land and Building Register (EGiB)	The building in reality
Building area	645 m^2	645 m^2
Total built-up area	16,770 m^2	20,804 m^2
Building intensity	20.8	25.8

Source: own work.

Due to the same building footprint, the built-up area is the same in both cases. The difference is noticeable in the total built-up area and building intensity. The ratios calculated on the basis of the EGiB are underestimated compared to the actual ratios given by the developer and are higher by 4,034 m^2 and 5.0, respectively.

Forest

The Land and Building Register (EGiB) analysis

According to the EGiB (Fig. 8), the built-up area of the Forest complex is 8,542 m^2, and its number of storeys is 28. The area of the plot on which it is located (20/4, precinct 6-03-02) is 19,616 m^2. Comparing this information to the actual state, an anomaly in the number of storeys can be seen. In fact, the building has 29 above-ground storeys and three underground storeys, which is not reflected in the EGiB data. The register also does not consider the fact that the campus consists of a high-rise section in a small area – the rest of the development is much lower. Due to the lack of distinction in the number of storeys, the outline shown in the EGiB misleadingly resembles a multi-family residential quarter rather than an office building.



Fig. 8. The Forest high-rise building in the Land and Building Register (EGiB)

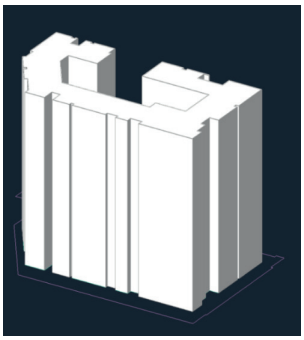
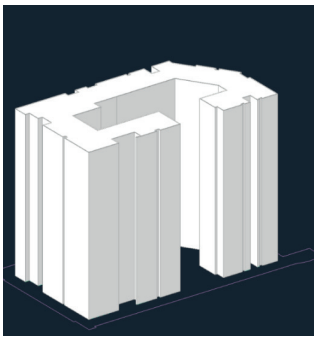
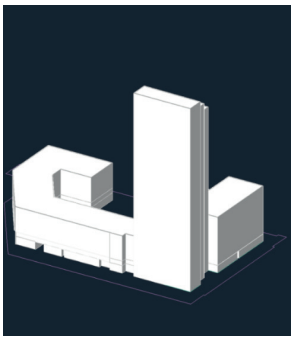
Source: GUGiK (2025).

Comparative model

The high-rise building model created based on the data in the EGiB shows the building as a uniform block (Table 9). It does not consider the architecturally complex massing, which is divided into sections with different

height and width segments. The concave elements of the building – such as the entrances to the building or the entrances to the underground garage noticeable at ground level – cause the building on the upper floors to adopt the same cut-outs. The EGiB, due to the two-dimensionality of the stored data, does not assume changes in volume with increasing height. This results in a significant difference between the model created from the records and the actual building.

Table 9. Models of Forest made in Autodesk Revit

The building according to the Land and Building Register (EGiB)		The building in reality	
			

Source: own work.

Both the model and the actual building have the same outline at ground level, so the built-up area is the same in both cases. The differences are visible in the total built-up area and amount to 160,186 m^2, which directly results in a much higher built-up intensity in the case of the model created from the records (Table 10).

Table 10. Differences in the parameters of the Forest models

Specification	The building according to the Land and Building Register (EGiB)	The building in reality
Building area	8,542 m^2	8,542 m^2
Total built-up area	239,176 m^2	78,990 m^2
Building intensity	12.2	4.0

Source: own work.

LIM Centre

The Land and Building Register (EGiB) analysis

According to the data in the Land Registry (Fig. 9), the built-up area of the LIM Centre high-rise building is 7,327 m² and its number of storeys is 43. The area of the plot on which it is located (3, precinct 5-05-01) is 13,384 m^2.



Built-up area: 7,327 m^2

Number of storeys: 43

Plot area: 13,384 m^2

Fig. 9. The LIM Centre high-rise building in the Land and Building Register (EGiB)

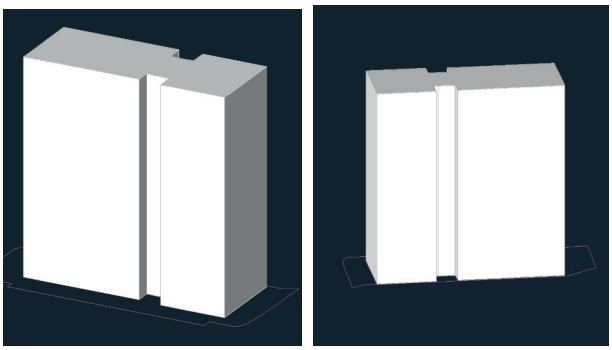
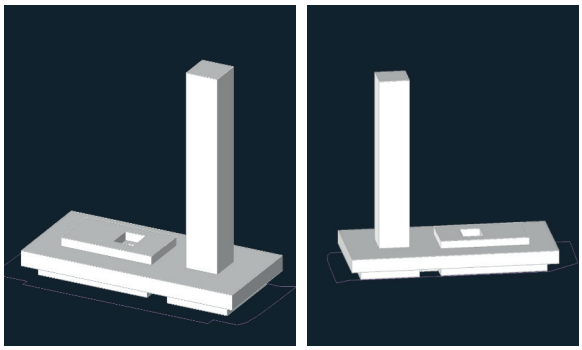
Source: GUGiK (2025).

When comparing this information to the actual state, inconsistencies in the number of storeys can be seen. In fact, the building has 42 above-ground storeys and two underground storeys, which is not reflected in the EGiB data. In addition, the number of above-ground storeys in the register is inconsistent with reality. The register also does not consider the fact that the high-rise building consists of a podium and a tower, which have a different number of storeys.

Comparative model

The model of the high-rise building created based on the data in the EGiB is much simplified and shows the building as a compact, uniform block with simple shapes (Table 11). It does not consider the more complex architecture of the actual building, which consists of a tall, slender tower set on an extended base with a much larger footprint. The model, according to the EGiB, omits important structural details such as the variety of massing within the base of the building and internal openings visible in the actual structure. The simplified form of the model does not fully reflect the proportions and distinctive segmentation that are central to the actual architecture of the building (Table 12).

Table 11. Models of the LIM Centre made in Autodesk Revit

The building according to the Land and Building Register (EGiB)	The building in reality
	

Source: own work.

Table 12. Differences in the parameters of the LIM Centre models

Specification	The building according to the Land and Building Register (EGiB)	The building in reality
Building area	7,327 m^2	7,327 m^2
Total built-up area	315,061 m^2	86,000 m^2
Building intensity	23.5	6.4

Source: own work.

Due to the same building footprint, the built-up area is the same in both cases. The difference can be seen in the total built-up area and amounts to 229,061 m^2, which directly affects the difference in building intensity of 17.1.

It should be noted that this approach can be used for secondary research, although the complexity of the building shape must be analysed individually in each case.

CONCLUSIONS

The analysis points out the inadequacies of the two-dimensional cadastre currently in use and highlights the opportunities presented by a multipurpose cadastre. The use of three-dimensional modelling in combination with the usual data available in the two-dimensional cadastre is insufficient and is responsible for the unrealistic results of urban indicators. Often, it is impossible to obtain the actual parameters needed to calculate these indicators in a given building, so they are calculated on the basis of the data available through the two-dimensional cadastre and turn out to be inconsistent with the actual state of affairs. Building structures are constructed in accordance with the design and are approved for use on the basis of appropriate control measurements (as-built survey). This raises the question of whether it is possible to use the actual three-dimensional model created as a result of measurements – e.g., laser scanning (photogrammetry) or BIM – or whether we should rather use design and construction data to build the model. In this context, should the results of actual field measurements or data from construction documentation be taken into account for the settlement of areas and their comparison with the cadastre? In the case of digital twins, it should be assumed that they will reflect the actual state very reliably; hence, geometrically and semantically correct BIM models could be used for fiscal purposes.

Therefore, the introduction of a multipurpose cadastre will avoid such inconsistencies. Another argument in favour of the introduction of a multipurpose cadastre, especially in cooperation with BIM, is the possibility of performing more accurate analyses of buildings, e.g. only a selected part of a building with a specific height, which is currently impossible due to the lack of such detailing in the two-dimensional cadastre. The introduction of a multidimensional and multipurpose cadastre in Poland would bring many benefits. The possibilities of integrating the cadastre with other technologies, such as BIM, for example, provide an opportunity to create a tool to support the effective management of urban space and development processes. However, the replacement of the two-dimensional cadastre with a multipurpose cadastre is associated with several challenges, including legal challenges, due to the need to refine the legal provisions through which the multipurpose cadastre could become the norm in the Polish cadastral system.

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Authors' contributions

Conceptualisation: A.S.B., A.D., P.G. and M.G.; methodology: A.S.B., A.D., P.G. and M.G.; validation: A.S.B.; formal analysis: A.S.B., A.D., P.G. and M.G.; resources: A.D., P.G. and M.G.; data curation: A.D., P.G. and M.G.; writing – original draft preparation: A.S.B., A.D., P.G. and M.G.; writing review and editing: A.S.B., A.D., P.G. and M.G.; visualisation: A.D., P.G. and M.G.; supervision: A.S.B.; funding acquisition: A.S.B.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Atazadeh, B., Olfat, H., Rajabifard, A., Kalantari, M., Shojaei, D. & Marjani, A. (2021). Linking Land Administration Domain Model and BIM environment for 3D digital cadastre in multi-storey buildings. *Land Use Policy*, *104*, 105367. https://doi.org/10.1016/j.landusepol.2021.105367

Baumane, V. (2010). Cadastral valuation models. *Economic Science for Rural Development*, *22*, 68–74.

Bennett, R., Rajabifard, A., Kalantari, M., Wallace, J. & Williamson, I. (2011, June). Cadastral futures: Building a new vision for the nature and role of cadastres. In *The XXIV FIG International Congress 2010 Proceedings*.

Borkowski, A. S., Osińska, N. & Szymańska, N. (2022). Przegląd dotychczasowych rozwiązań na poziomie aplikacyjnym w zakresie integracji technologii BIM i GIS. *Builder*, *305* (12), 64–69.

Borkowski, A. S. & To Duc, A. (2024). Integration of BIM and GIS data of a heritage building using FME. *Civil and Environmental Engineering Reports*, *2* (34), 204–215.

Borkowski, A. S., Adamczyk, N., Gadosz, J. & Marynowski, M. (2025). Badanie możliwości zasilania katastru wielowymiarowego danymi z systemów BIM. *Przegląd Geodezyjny*, *97* (4), 21–25.

Bydłosz, J. (2012). Kataster wielowymiarowy na świecie i uwarunkowania jego implementacji w Polsce. *Roczniki Geomatyki*, *10* (3), 47–54.

Etel, L. (Ed.), Dowgier, R., Liszewski, G., Popławski, M. & Presnarowicz, S. (2008). *Prawo podatkowe*. Warszawa: Difin.

Główny Urząd Geodezji i Kartografii [GUGiK] (2025). Homepage National Geoportal. Retrieved from Geoportal.gov.pl [accessed: 13.01.2025].

HB Reavis (2023). *Zakończyliśmy budowę kampusu biurowego Forest*. ForestCampus.pl. Retrieved from https://forestcampus.pl/zakonczylismy-budowe-kampusu-biurowego-forest/ [accessed: 13.01.2025].

International Federation of Surveyors [FIG] (1998). *The FIG Statement on the Cadastre* (Publication 11). Frederiksberg: FIG. Retrieved from https://www.fig.net/resources/publications/figpub/pub11/FIG%20Statement%20on%20the%20Cadastre.pdf [accessed: 12.01.2025].

Kjartansdóttir, I. B., Mordue, S., Nowak, P., Philp, D. & Snæbjörnsson, J. T. (2017). *Building Information Modelling – BIM*. Warsaw: Warsaw University of Technology.

Knight Frank (2025, June 12). *Central Tower*. SpaceFinder.pl. Retrieved from https://officepoland.pl/biura-do-wynajecia/warszawa/central-tower/92-2/ [accessed: 13.01.2025].

Kopyściańska, K. (2017). Podatek katastralny w Polsce – czy słuszna koncepcja? [Cadastral tax in Poland – is it the right concept?]. *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu*, *485*, 240–250

Li, X. & Gar-On Yeh, A. (2000). Modelling sustainable urban development by the integration of constrained cellular automata and GIS. *International Journal of Geographical Information Science*, *14*, 131–152.

LIM Center (2021). Homepage Lim.pl. Retrieved from https://lim.pl/ [accessed: 12.01.2025].

Noszczyk, T. & Hernik, J. (2019). Understanding the cadastre in rural areas in Poland after the socio-political transformation. *Journal of Spatial Science*, *64* (1), 73–95.

Puls Biznesu (2022, June 8). *Złota 44 kończy komercjalizację budynku – spektakularna transakcja*. PB.pl. Retrieved from https://www.pb.pl/zlota-44-konczy-komercjalizacje-budynku-spektakularna-transakcja-1152724 [accessed: 13.01.2025].

Rondo 1 (2025). *Homepage Rondo1.pl*. Retrieved from https://www.rondo1.pl/budynek/ [accessed: 13.01.2025].

Rozporządzenie Ministra Rozwoju, Pracy i Technologii z dnia 27 lipca 2021 r. w sprawie bazy danych obiektów topograficznych oraz bazy danych obiektów ogólnogeograficznych, a także standardowych opracowań kartograficznych (Dz.U. 2021 poz. 1412).

Sarniewicz, M. (2022, March 28). *Forest – HB Reavis zakończył budowę kompleksu Forest w Warszawie*. Murator Plus. Retrieved from https://www.muratorplus.pl/inwestycje/inwestycje-komercyjne/hb-reavis-forest-w-warszawie-taras-na-dachu-aa-Uw31-kR2J-hvcp.html [accessed: 13.01.2025].

Skysawa (2025, January 12). *Homepage SkySawa.pl*. Retrieved from https://skysawa.pl/ [accessed: 12.01.2025].

Sun, J., Mi, S., Olsson, P., Paulsson, J. & Harrie, L. (2019). Utilizing BIM and GIS for representation and visualization of 3D cadastre. *International Journal of Geo-Information*, *8* (11), 503. https://doi.org/10.3390/ijgi8110503

Urbanity (2021, January 29). *Rondo 1 – Warszawa*. Urbanity.pl. Retrieved from https://www.urbanity.pl/mazowieckie/warszawa/rondo-1,b1272 [accessed: 13.01.2025].

Urbanity (2025, January 7). *Centrum LIM – Warszawa*. Urbanity.pl. Retrieved from https://www.urbanity.pl/mazowieckie/warszawa/centrum-lim,b6 [accessed: 13.01.2025].

Uşak, B., Çağdaş, V. & Kara, A. (2024). Current cadastral trends – A literature review of the last decade. *Land*, *13* (12), 2100. https://doi.org/10.3390/land13122100

Wang, H., Pan, Y. & Luo, X. (2019). Integration of BIM and GIS in sustainable built environment: A review and bibliometric analysis. *Automation in Construction*, *103*, 41–52.

Złota 44 (2025, January 13). *Inwestycja*. Retrieved from http://zlota44.com/inwestycja/ [accessed: 13.01.2025].

ANALIZA PORÓWNAWCZA MODELI BUDYNKÓW WYSOKOŚCIOWYCH JAKO ŹRÓDŁA DANYCH DLA KATASTRU WIELOWYMIAROWEGO

STRESZCZENIE

W artykule przedstawiono problem związany z ograniczeniami obecnej formy katastru stosowanej w Polsce – katastru dwuwymiarowego, która często nie jest wystarczająca w obliczu rozwoju technologicznego. Problem ten został przedstawiony za pomocą analizy porównawczej sześciu wybranych warszawskich budynków wysokościowych, które cechują się złożoną geometrią bryły: Rondo 1, Skysawa, Złota 44, Central Tower, Forest oraz Centrum LIM. We wprowadzeniu został poruszony temat ograniczeń katastru dwuwymiarowego, a także szans, jakie ze sobą niesie kataster wielozadaniowy, który dzięki integracji z systemami GIS i technologią BIM może być rewolucją w polskim systemie katastralnym. W części analitycznej, za pomocą danych dostępnych w Ewidencji gruntów i budynków (EGiB) oraz dostępnych danych o rzeczywistej bryle, w programie Revit stworzono po dwa modele każdego analizowanego wieżowca, aby bliżej zaprezentować niedokładności katastru dwuwymiarowego. Wyliczone według EGiB wskaźniki urbanistyczne zostały porównane również ze wskaźnikami rzeczywistymi, co potwierdziło, że kataster w obecnej formie jest niewystarczający do rzetelnego zobrazowania rzeczywistości.

Słowa kluczowe: kataster wielowymiarowy, wieżowiec, BIM

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HU–WASHIZU VARIATIONAL PRINCIPLE IN PROBLEMS OF STABILITY OF NON-THIN ANISOTROPIC CYLINDRICAL SHELLS MADE OF MODERN COMPOSITE MATERIALS IN SPATIAL FORMULATION

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ABSTRACT

In this study, the Hu–Washizu variational principle was employed to derive a three-dimensional system of partial differential equations, which governs the stability of an anisotropic body. This system was expressed in the cylindrical coordinate system. The analytical Bubnov–Galerkin method was employed to reduce it to a one-dimensional one. The solution of the one-dimensional problem in the direction of the normal to the median surface of the shell structure was carried out using the numerical method of discrete orthogonalisation. The present study investigates the values of critical loads of external lateral pressure for an anisotropic cylindrical shell made of a fibrous composite and the same shell with a layer of a functionally graded material. The study investigates the dependence of the critical loads on the angle of rotation of the main elastic directions of the unidirectional fibrous material and the number of its layers. The findings of this study demonstrate that incorporating a functionally graded material layer has the potential to enhance the critical loads of the structure.

Keywords: anisotropic laminated shell, fibrous composite, functionally graded material, critical load, spatial formulation

INTRODUCTION

Resolving problems in the theory of elasticity and structural mechanics is closely related to the utilisation of variational principles (Tonti, 1967; Abovsky, Andreev & Deruga, 1978; Washizu, 1982; Lanczos, 1986), which can be employed to create new consistent models for calculating shell structures. The utilisation of variational principles is also associated with the finite element method, a widely employed technique in the design of contemporary engineering structures (Zienkiewicz, 1972; Bazhenov, Kryvenko & Solovey, 2010; Kryvenko, Lizunov, Vorona & Kalashnikov, 2024). The development of classical and refined theories for calculating shell structures has been enabled by the adoption of variational methods (Grigorenko & Kryukov, 1988; Bazhenov, Semenyuk & Trach, 2010; Trach, Podvorny & Khoruzhiy, 2019). These theories have been instrumental in facilitating the acquisition of reliable solutions to problems concerning the stress–strain state and the stability and dynamics of anisotropic shells. However, the use of modern composite materials in modern engineering

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increases the demands on the construction of mathematical models and, consequently, the need for more accurate calculation approaches. For example, modern functionally graded materials (FGMs) are heterogeneous anisotropic composites consisting of different phases of material components. The widespread use of FGMs in various fields of modern engineering requires the development of approaches (Reddy, 2000; Lee, Zhao & Reddy, 2010; Kołakowski & Mania, 2012; Kowal-Michalska & Mania, 2013) that make it possible to fully consider the properties of such materials under different types of impacts. The use of FGMs as materials for shell structures requires consideration of changes in their structure, such as thickness, which can be done using the relations of the spatial theory of elasticity. A substantial corpus of works has been dedicated to resolving issues pertaining to the stability of shell structures composed of isotropic and orthotropic materials in three dimensions. Among these, the most comprehensive and generalised are the scientific works (Guz & Babich, 1980; Guz & Babich, 1985; Guz, 1986) in which the problems of the three-dimensional stability of cylindrical shells made of orthotropic materials under external forces are solved. However, the advent of modern composite materials has necessitated the refinement of methodologies for addressing these stability concerns. This discrepancy may be attributed to the disparity between the predominant elasticity orientations of the pre-orthotropic material and the curvilinear coordinate system employed in the shells (Fig. 1).

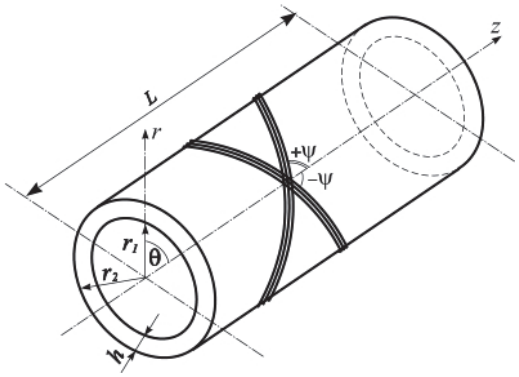


Fig. 1. Anisotropic non-thin cylindrical shell (ψ – rotation angle; z, θ, r – coordinates, r_1 – radius of the inner surface, r_2 – radius of the outer surface, L – length of the cylinder's base, h – wall thickness of the cylinder)

Source: Semenyuk, Trach and Podvornyi (2023).

The complexity of creating approaches to calculate such shell structures is caused by the interconnection of tensile (compression) and shear, bending, and torsion deformations, which leads to more complex equations of subcritical stress–strain state and stability compared to orthotropic ones (Ambartsumyan, 1974; Lekhnitskii, 1981; Trach, Semenuk & Podvornyi, 2016; Podvornyi, Semenyuk & Trach, 2017; Semenyuk, Trach & Podvornyi, 2019; Trach et al., 2019; Trach, Podvorny & Zhukova, 2023). This paper proposes an approach to modifying the functional of the generalised Hu–Washizu variational principle to a form that considers the peculiarities of modern materials and is based on the relations of the theory of elasticity of an anisotropic body. The elastic properties of these materials are confined to a single plane of elastic symmetry.

BASIC EQUATIONS. THE HU–WASHIZU PRINCIPLE OF VARIATIONS

In accordance with the Hu–Washizu variational principle (Washizu, 1982), it can be demonstrated that the equilibrium equation, stability equation, elasticity relations, geometric relations and corresponding

boundary conditions can be obtained from the stationarity condition of the functional Π_1, which is defined from the integral:

$$\Pi_1 = \iiint_V \left\{ W\left(e_{ij}\right) + \Phi\left(u_i\right) - \sigma_{ij}\left[e_{ij} - \frac{1}{2}\left(u_{i,j} + u_{j,i}\right)\right]\right\} dV + \iint_{S_1} \Psi\left(u_i\right) dS_1 - \iint_{S_2} p_i\left(u_i - \overline{u}_i\right) dS_2, \tag{1}$$

where (without additional conditions):
u_i – displacements,
e_{ij} – defined in terms of the deformation components ε_{ij} from the geometrically linear theory of elasticity,
σ_{ij} – stresses on the surface S_1,
p_i – stresses on the surface S_2 (varied), induced by the displacements $\overline{u}_i$,
$W(e_{ij})$ – potential energy of deformation,
$\Phi(u_i)$, $\Psi(u_i)$ – volumetric and surface load potentials, respectively, the semicolon before the parameters i, j denotes the covariant derivative at the coordinate with the corresponding index i, j = 1, 2, 3, where 1 corresponds to coordinate z, 2 to coordinate θ, and 3 to coordinate r (Fig. 1),
V – volume of the casing material.

The strain energy potential, as represented by the vector-matrix notation, is expressed as follows:

$$W\left(e_{ij}\right) = \frac{1}{2}\varepsilon^T B\varepsilon, \tag{2}$$

where:
$\varepsilon^T = (\varepsilon_{zz}, \varepsilon_{\theta\theta}, \varepsilon_{rr}, 2\varepsilon_{r\theta}, 2\varepsilon_{rz}, 2\varepsilon_{z\theta})$ – vector of deformation components in the geometrically linear theory of elasticity,
B – elasticity matrix.

In accordance with work by Washizu (1982), the following equations can be derived by applying the stationarity condition of $\delta\Pi_1$ and introducing the vector $\sigma^T = (\sigma_{zz}, \sigma_{\theta\theta}, \sigma_{rr}, \sigma_{r\theta}, \sigma_{rz}, \sigma_{z\theta})$:
1. For the elasticity relation, the equation takes the form:

$$\sigma = B\varepsilon. \tag{3}$$

2. For geometric relationships, the equation takes the form:

$$\varepsilon = \varepsilon(u). \tag{4}$$

3. For equilibrium equations, the equation takes the form:

$$\sigma_{ij,j} + f_i = 0. \tag{5}$$

Additionally, the boundary conditions $\sigma_{ij}n_j = \overline{F}_i$ on the surface S_1 as well as the displacements $u_i = \overline{u}_i$ and stresses $p_i = \sigma_{ij}n_j$ on the surface S_2 can also be obtained.

In the dependencies for deformations, (4) shows the relationship between deformations and displacements. In the inverse of the elasticity relations (3), the strain–stress dependence is represented as:

$$\varepsilon = A\sigma, \tag{6}$$

where Matrix $A = B^{-1}$.

Coefficients of the Matrix A will be denoted as a_{ij}, and the Matrix B as b_{ij} $(i, j = \overline{1,6})$. Matrices A and B are symmetrical, because $a_{ij} = a_{ji}$, $b_{ij} = b_{ji}$.

Modification of the mixed variational principle in deriving the equations of subcritical stress–strain state

To develop the modified Hu–Washizu mixed variational principle, we divide the vectors σ and ε into two parts:

$$\begin{aligned} \sigma_1^T &= (\sigma_{rr}, \tau_{r\theta}, \tau_{rz}), \qquad \sigma_2^T = (\sigma_{zz}, \sigma_{\theta\theta}, \tau_{z\theta}), \\ \varepsilon_1^T &= (\varepsilon_{rr}, \varepsilon_{r\theta}, \varepsilon_{rz}), \qquad \varepsilon_2^T = (\varepsilon_{zz}, \varepsilon_{\theta\theta}, \varepsilon_{z\theta}). \end{aligned} \tag{7}$$

The physical relationship (6) is written as a matrix:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \end{bmatrix}. \tag{8}$$

In relationship (8), the blocks A_{ij} are formed in accordance with the structure given in (7) and (8), for the case of an anisotropic material whose elastic properties are characterised by a single plane of elastic symmetry (Ambartsumyan, 1974), and taking that into account, in the case of elastic deformations, $a_{ij} = a_{ji}$:

$$\begin{aligned} A_{11} &= \begin{bmatrix} a_{33} & 0 & 0 \\ 0 & a_{44} & a_{45} \\ 0 & a_{45} & a_{55} \end{bmatrix}, \qquad A_{12} = \begin{bmatrix} a_{13} & a_{23} & a_{36} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \\ A_{21} &= \begin{bmatrix} a_{13} & 0 & 0 \\ a_{23} & 0 & 0 \\ a_{36} & 0 & 0 \end{bmatrix}, \qquad A_{22} = \begin{bmatrix} a_{11} & a_{12} & a_{16} \\ a_{12} & a_{22} & a_{26} \\ a_{16} & a_{26} & a_{66} \end{bmatrix}. \end{aligned} \tag{9}$$

From dependence (6), using (8), we obtain:

$$\varepsilon_1 = A_{11}\sigma_1 + A_{12}\sigma_2, \tag{10}$$

$$\varepsilon_2 = A_{21}\sigma_1 + A_{22}\sigma_2. \tag{11}$$

From equation (11), we obtain:

$$\sigma_2 = A_{22}^{-1}\varepsilon_2 - A_{22}^{-1}A_{21}\sigma_1. \tag{12}$$

Substituting (12) into (10), we obtain:

$$\varepsilon_1 = A_{11}\sigma_1 + A_{12}A_{22}^{-1}\varepsilon_2 - A_{12}A_{22}^{-1}A_{21}\sigma_1 = A_{12}A_{22}^{-1}\varepsilon_2 + \left(A_{11} - A_{12}A_{22}^{-1}A_{21}\right)\sigma_1. \tag{13}$$

We obtain the following from the dependence (13):

$$\sigma_1 = \left(A_{11} - A_{12}A_{22}^{-1}A_{21}\right)^{-1} \cdot \varepsilon_1 - \left(A_{11} - A_{12}A_{22}^{-1}A_{21}\right)^{-1} \cdot A_{12}A_{22}^{-1}\varepsilon_2. \tag{14}$$

The matrix expression (3) is hereby represented in the following manner:

$$\begin{bmatrix}\sigma_1\\ \sigma_2\end{bmatrix}=\begin{bmatrix}B_{11} & B_{12}\\ B_{21} & B_{22}\end{bmatrix}\cdot\begin{bmatrix}\varepsilon_1\\ \varepsilon_2\end{bmatrix}. \tag{15}$$

The subsequent course of action is to be pursued in accordance with the methodology delineated in the paper by Semenyuk et al. (2023). We establish the relationship between the Matrices A and B. Then the dependence for the potential strain energy $W(e_{ij})$ can be written in the following form:

$$W_1 = W\left(\sigma_1,\varepsilon_2\right)-\sigma_{ij}\left(\varepsilon_{ij}-\varepsilon_{ij}\left(u\right)\right)=$$
$$=-\frac{1}{2}\sigma_1^T B_{11}^{-1}\sigma_1-\frac{1}{2}\varepsilon_2^T\left(B_{22}-B_{12}^T B_{11}^{-1}B_{12}\right)\varepsilon_2+\left(\varepsilon_1^T\left(u\right)+\varepsilon_2^T\left(u\right)B_{12}^T B_{11}^{-1}\right)\sigma_1+\varepsilon_2^T\left(u\right)\left(B_{22}-B_{12}^T B_{11}^{-1}B_{12}\right)\varepsilon_2. \tag{16}$$

In accordance with the objective set forth in the present work, the potential of volumetric loads $\Phi(u_i)$ is neglected.

Considering the above, we write down the final form of the functionality Π_1, which is presented in (1), as follows:

$$\Pi_1=\iiint_V\left[W\left(\sigma_1,\varepsilon_2\right)\right]dV+\iint_{S_1}\Psi\left(u_i\right)dS_1-\iint_{S_2}p_i\left(u_i-\overline{u}_i\right)dS_2. \tag{17}$$

The dependence for Π_1 demonstrates the part presents the part of this functionality (1), because it replaces the number of independent variables by fulfilling the condition $\varepsilon_2 = \varepsilon_2(u)$. Taking this into account, the direct determination of the variation of the functional (17), which is caused by changes in the components of the displacement vector u and the stresses σ_1, takes the following form:

$$\delta\Pi_1=\iiint_V\left\{\left[-\frac{1}{2}\sigma_1^T B_{11}^{-1}\sigma_1+\left(\varepsilon_1^T(u)+\varepsilon_2(u)B_{11}^T B_{12}^{-1}\right)\sigma_1\right]\delta\sigma_1-\left[\frac{1}{2}\varepsilon_2^T\left(B_{22}-B_{12}^T B_{11}^{-1}B_{12}\right)\varepsilon_2\right]\delta\varepsilon_2+\right.$$
$$\left.+\left[\varepsilon_2^T\left(u\right)\left(B_{22}-B_{12}^T B_{11}^{-1}B_{12}\right)\varepsilon_2\right]\delta u\right\}dV+\iint_{S_1}\Psi\left(u_i\right)dS_1-\iint_{S_2}p_i\left(u_i-\overline{u}_i\right)dS_2. \tag{18}$$

For further transformations, we will use the geometric Cauchy relations (Novozhilov, 1961):

$$\varepsilon_{zz}=\frac{\partial u_z}{\partial z},\ \varepsilon_{\theta\theta}=\frac{1}{r}\frac{\partial u_\theta}{\partial\theta}+\frac{1}{r}u_r,\ \varepsilon_{rr}=\frac{\partial u_r}{\partial r},$$
$$\varepsilon_{z\theta}=\frac{\partial u_\theta}{\partial z}+\frac{1}{r}\frac{\partial u_z}{\partial\theta},\ \varepsilon_{rz}=\frac{\partial u_r}{\partial z}+\frac{\partial u_z}{\partial r},\ \varepsilon_{r\theta}=\frac{\partial u_\theta}{\partial r}-\frac{1}{r}u_\theta+\frac{1}{r}\frac{\partial u_r}{\partial\theta}, \tag{19}$$

where:

e_{rr}, e_{zz}, $e_{\theta\theta}$ – relative linear deformations in the directions of the axes of the coordinates z, θ, r, respectively (Fig. 1),

e_{rz}, $e_{r\theta}$, $e_{z\theta}$ – relative shear deformations tangent to the corresponding coordinate surfaces.

When considering the stationarity of the expression for the variation of the functional (18), use the dependencies for stresses $\sigma_1^T=\left(\sigma_{rr},\tau_{r\theta},\tau_{rz}\right)$, displacements $u^T=\left(u_r,u_\theta,u_z\right)$ and the geometric relationships (19). After equating the expressions for the independent variations of stresses $\delta\sigma_{rr}$, $\delta\tau_{r\theta}$, $\delta\tau_{rz}$ and displacements δu_r, δu_θ, δu_z in the volume integral V to 0, using the Euler–Lagrange method, we obtain equations describing the pre-critical stress–strain state of a cylindrical anisotropic shell in a spatial formulation:

$$\frac{\partial \sigma_{rr}}{\partial r} = -\frac{c_{23}+1}{r}\sigma_{rr} - \frac{\partial \tau_{rz}}{\partial z} - \frac{1}{r}\frac{\partial \tau_{r\theta}}{\partial \theta} + \frac{c_{22}}{r^2}u_r + \frac{c_{12}}{r}\frac{\partial u_z}{\partial z} + \frac{c_{26}}{r^2}\frac{\partial u_z}{\partial \theta} + \frac{c_{26}}{r}\frac{\partial u_\theta}{\partial z} + \frac{c_{22}}{r^2}\frac{\partial u_\theta}{\partial \theta},$$

$$\frac{\partial \tau_{rz}}{\partial r} = c_{13}\frac{\partial \sigma_{rr}}{\partial z} - \frac{1}{r}\tau_{rz} - \frac{c_{12}}{r}\frac{\partial u_r}{\partial z} - c_{11}\frac{\partial^2 u_z}{\partial z^2} - \frac{c_{66}}{r^2}\frac{\partial^2 u_z}{\partial \theta^2} - \frac{c_{12}+c_{66}}{r}\frac{\partial^2 u_\theta}{\partial z \partial \theta} + \frac{c_{36}}{r}\frac{\partial \sigma_{rr}}{\partial \theta} -$$
$$- \frac{c_{26}}{r^2}\frac{\partial u_r}{\partial \theta} - \frac{2c_{16}}{r}\frac{\partial^2 u_z}{\partial z \partial \theta} - c_{16}\frac{\partial^2 u_\theta}{\partial z^2} - \frac{c_{26}}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2},$$

$$\frac{\partial \tau_{r\theta}}{\partial r} = \frac{c_{23}}{r}\frac{\partial \sigma_{rr}}{\partial \theta} - \frac{2}{r}\tau_{r\theta} - \frac{c_{22}}{r^2}\frac{\partial u_r}{\partial \theta} - \frac{c_{12}+c_{66}}{r}\frac{\partial^2 u_z}{\partial z \partial \theta} - c_{66}\frac{\partial^2 u_\theta}{\partial z^2} - \frac{c_{22}}{r^2}\frac{\partial^2 u_\theta}{\partial \theta^2} +$$
$$+ c_{36}\frac{\partial \sigma_{rr}}{\partial z} - \frac{c_{26}}{r}\frac{\partial u_r}{\partial z} - c_{16}\frac{\partial^2 u_z}{\partial z^2} - \frac{c_{26}}{r^2}\frac{\partial^2 u_z}{\partial \theta^2} - \frac{2c_{26}}{r}\frac{\partial^2 u_\theta}{\partial z \partial \theta},$$

$$\frac{\partial u_r}{\partial r} = c_{33}\sigma_{rr} + \frac{c_{23}}{r}u_r + c_{13}\frac{\partial u_z}{\partial z} + \frac{c_{36}}{r}\frac{\partial u_z}{\partial \theta} + c_{36}\frac{\partial u_\theta}{\partial z} + \frac{c_{23}}{r}\frac{\partial u_\theta}{\partial \theta},$$

$$\frac{\partial u_z}{\partial r} = a_{55}\tau_{rz} + a_{45}\tau_{r\theta} - \frac{\partial u_r}{\partial z},$$

$$\frac{\partial u_\theta}{\partial r} = a_{45}\tau_{rz} + a_{44}\tau_{r\theta} - \frac{1}{r}\frac{\partial u_r}{\partial \theta} + \frac{1}{r}u_\theta, \tag{20}$$

where:

r – radial coordinate,

σ_{rr}, τ_{rz}, $\tau_{r\theta}$ – stress tensor components,

u_z, u_θ, u_r – movement of the shell observed in the directions corresponding to the axes of the cylindrical coordinate system z, θ, r, respectively (Fig. 1),

c_{kl} (k, l = 1, 2, 3, 6) – constant, which is the characteristics determined by the mechanical constant a_{kl} (Lekhnitskii, 1981) of the shell material:

$$c_{11} = \frac{1}{|A_{22}|}\left(a_{22}a_{66} - a_{26}^2\right),\ c_{12} = \frac{1}{|A_{22}|}\left(a_{16}a_{26} - a_{12}a_{66}\right),$$

$$c_{22} = \frac{1}{|A_{22}|}\left(a_{11}a_{66} - a_{16}^2\right),\ c_{16} = \frac{1}{|A_{22}|}\left(a_{12}a_{26} - a_{22}a_{16}\right),$$

$$c_{26} = \frac{1}{|A_{22}|}\left(a_{12}a_{16} - a_{11}a_{26}\right),\ c_{66} = \frac{1}{|A_{22}|}\left(a_{11}a_{22} - a_{12}^2\right),$$

$$|A_{22}| = a_{66}\left(a_{11}a_{22} - a_{12}^2\right) + a_{26}\left(a_{12}a_{16} - a_{11}a_{26}\right) + a_{16}\left(a_{12}a_{26} - a_{22}a_{16}\right),$$

$$c_{22} = \frac{1}{|A_{22}|}\left(a_{11}a_{66} - a_{16}^2\right),\ c_{16} = \frac{1}{|A_{22}|}\left(a_{12}a_{26} - a_{22}a_{16}\right),$$

$$c_{26} = \frac{1}{|A_{22}|}\left(a_{12}a_{16} - a_{11}a_{26}\right),\ c_{66} = \frac{1}{|A_{22}|}\left(a_{11}a_{22} - a_{12}^2\right), \tag{21}$$

The three-dimensional system of differential equations describing the subcritical stress–strain state of anisotropic cylindrical shells in the spatial formulation and its solution are carried out according to the methodology presented in the paper by Semenyuk et al. (2023).

Modification of the mixed variational principle in the derivation of stability equations

The elastic potential (16) is represented to derive the system of differential equations of stability:

$$W_1 = -\frac{1}{2}\sigma_1^T B_{11}^{-1}\sigma_1 - \frac{1}{2}\varepsilon_2^T\left(B_{22} - B_{12}^T B_{11}^{-1} B_{12}\right)\varepsilon_2 + \left(\varepsilon_1^T(u) + \varepsilon_2^T(u) B_{12}^T B_{11}^{-1}\right)\sigma_1 + \\ + \varepsilon_2^T(u)\left(B_{22} - B_{12}^T B_{11}^{-1} B_{12}\right)\varepsilon_2. \tag{22}$$

To derive the system of differential stability equations, we represent the elastic potential (16) in the form (22) and use the expansions (Novozhilov, 1961):

$$\sigma_1 = \sigma_1^0 + \alpha\sigma_1^{(1)} + \alpha^2\sigma_1^{(2)}, \\ \varepsilon_1 = \varepsilon_1^0 + \alpha\varepsilon_1^{(1)} + \alpha^2\varepsilon_1^{(2)}, \\ \varepsilon_2 = \varepsilon_2^0 + \alpha\varepsilon_2^{(1)} + \alpha^2\varepsilon_2^{(2)}. \tag{23}$$

In this context, the components of the stress–strain state with a zero subscript represent the pre-critical values of deformations and stresses, obtained after solving system (20), which describes the pre-critical stress–strain state of a cylindrical anisotropic shell in a spatial formulation. On another note, those elements with an index of one are considered perturbed. Finally, components indicated by a number two remain constant but are squared; α is an infinitesimal constant that is independent of the coordinates of the adopted coordinate system of the shell structure.

After substituting (23) into (22) and performing the appropriate transformations, we obtain the following expression for the potential strain energy:

$$W_1 = -\frac{1}{2}\left(\sigma_1^0 + \alpha\sigma_1^{(1)} + \alpha^2\sigma_1^{(2)}\right)^T B_{11}^{-1}\left(\sigma_1^0 + \alpha\sigma_1^{(1)} + \alpha^2\sigma_1^{(2)}\right) - \frac{1}{2}\left(\varepsilon_2^0 + \alpha\varepsilon_2^{(1)} + \alpha^2\varepsilon_2^{(2)}\right)^T \times \\ \times\left(B_{22} - B_{12}^T B_{11}^{-1} B_{12}\right)\left(\varepsilon_2^0 + \alpha\varepsilon_2^{(1)} + \alpha^2\varepsilon_2^{(2)}\right) + \left[\left(\varepsilon_1^0 + \alpha\varepsilon_1^{(1)} + \alpha^2\varepsilon_1^{(2)}\right)^T + \left(\varepsilon_2^0 + \alpha\varepsilon_2^{(1)} + \alpha^2\varepsilon_2^{(2)}\right)^T B_{12}^T B_{11}^{-1}\right] \times \\ \times\left(\sigma_1^0 + \alpha\sigma_1^{(1)} + \alpha^2\sigma_1^{(2)}\right) + \left(\varepsilon_2^0 + \alpha\varepsilon_2^{(1)} + \alpha^2\varepsilon_2^{(2)}\right)^T \times \left(B_{22} - B_{12}^T B_{11}^{-1} B_{12}\right)\left(\varepsilon_2^0 + \alpha\varepsilon_2^{(1)} + \alpha^2\varepsilon_2^{(2)}\right). \tag{24}$$

After performing a series of mathematical transformations using equations (24) and (19) and applying the variation operation, the varied functional is obtained. By setting the coefficients of the independent variations of the displacements and stresses to zero, a linearised system of stability equations for anisotropic cylindrical shells is derived:

$$\frac{\partial\sigma_{rr}}{\partial r} = -\frac{c_{23}+1}{r}\sigma_{rr} - \frac{1}{r}\frac{\partial\tau_{r\theta}}{\partial\theta} - \frac{\partial\tau_{rz}}{\partial z} + \frac{c_{12}}{r}\frac{\partial u_z}{\partial z} + \frac{c_{22}}{r^2}u_r + \frac{c_{22}}{r^2}\frac{\partial u_\theta}{\partial\theta} + \frac{c_{26}}{r^2}\frac{\partial u_z}{\partial\theta} + \frac{c_{26}}{r}\frac{\partial u_\theta}{\partial z} + \\ + \left(-\frac{\partial u_z}{\partial z}c_{13} - \frac{1}{r}\left(\frac{\partial u_\theta}{\partial\theta} + u_r\right)c_{23} - \left(\frac{\partial u_\theta}{\partial z} + \frac{1}{r}\frac{\partial u_z}{\partial\theta}\right)c_{36} - \sigma_{rr}c_{33} - \frac{2}{r}\frac{\partial u_\theta}{\partial\theta}c_{23} - \frac{1}{r}u_r c_{23} - \right. \\ \left. - 2\frac{\partial u_\theta}{\partial z}c_{36}\right)\sigma_{rr}^0 + \left(-2\frac{\partial u_r}{\partial z}c_{23} + \frac{\partial\sigma_{rr}}{\partial z}c_{33} - \frac{\partial u_r}{\partial z}\right)\tau_{rz}^0 + \left(-\frac{2}{r}\frac{\partial u_r}{\partial\theta}c_{23} + \frac{\partial\sigma_{rr}}{\partial\theta}c_{33} - \frac{1}{r}\frac{\partial u_r}{\partial\theta} + \frac{1}{r}u_\theta\right)\tau_{r\theta}^0,$$

$$\frac{\partial\tau_{rz}}{\partial r} = \frac{\partial\sigma_{rr}}{\partial z}c_{13} + \frac{1}{r}\frac{\partial\sigma_{rr}}{\partial\theta}c_{36} - \frac{1}{r}\tau_{rz} - \frac{c_{12}}{r}\frac{\partial u_r}{\partial z} - \frac{c_{26}}{r^2}\frac{\partial u_r}{\partial\theta} + \left(\frac{\partial u_r}{\partial z} - \tau_{r\theta}a_{45} - \tau_{rz}a_{55}\right)\sigma_{rr}^0 + \\ + \left(-2r\left(\frac{\partial\tau_{r\theta}}{\partial z}a_{45} + \frac{\partial\tau_{rz}}{\partial z}a_{55}\right) - \frac{\partial u_z}{\partial z}\right)\tau_{rz}^0 + \left(-2\left(+\frac{\partial\tau_{r\theta}}{\partial\theta}a_{45} + \frac{\partial\tau_{rz}}{\partial\theta}a_{55}\right) - \frac{1}{r}\frac{\partial u_z}{\partial\theta}\right)\tau_{r\theta}^0,$$

$$\frac{\partial \tau_{r\theta}}{\partial r} = \frac{1}{r}\frac{\partial \sigma_{rr}}{\partial \theta}c_{23} + \frac{\partial \sigma_{rr}}{\partial z}c_{36} - \frac{2}{r}\tau_{r\theta} - \frac{c_{22}}{r^2}\frac{\partial u_r}{\partial \theta} - \frac{c_{26}}{r}\frac{\partial u_r}{\partial z} + \left(-\frac{1}{r}u_\theta + \frac{1}{r}\frac{\partial u_r}{\partial \theta} - \tau_{r\theta}a_{44} - \right.$$
$$\left. - \tau_{rz}a_{45} + \frac{2}{r}\frac{\partial u_r}{\partial \theta}c_{23} - \frac{1}{r}u_\theta c_{23} + 2\frac{\partial u_r}{\partial z}c_{36}\right)\sigma_{rr}^0 + \left(-2r\left(\frac{1}{r}\frac{\partial u_\theta}{\partial z} + \frac{\partial \tau_{r\theta}}{\partial z}a_{44} + \frac{\partial \tau_{rz}}{\partial z}a_{45}\right) - \right.$$
$$\left. - \frac{\partial u_\theta}{\partial z}\right)\tau_{rz}^0 + \left(-2r\left(\frac{1}{r}\frac{\partial u_\theta}{\partial \theta} + \frac{\partial \tau_{r\theta}}{\partial \theta}a_{44} + \frac{\partial \tau_{rz}}{\partial \theta}a_{45}\right) - \frac{1}{r}\frac{\partial u_\theta}{\partial \theta} - \frac{1}{r}u_r\right)\tau_{r\theta}^0,$$
$$\frac{\partial u_r}{\partial r} = \frac{\partial u_z}{\partial z}c_{13} + \frac{1}{r}\left(\frac{\partial u_\theta}{\partial \theta} + u_r\right)c_{23} + \left(\frac{\partial u_\theta}{\partial z} + \frac{1}{r}\frac{\partial u_z}{\partial \theta}\right)c_{36} + \sigma_{rr}c_{33},$$
$$\frac{\partial u_z}{\partial r} = -\frac{\partial u_r}{\partial z} + \tau_{r\theta}a_{45} + \tau_{rz}a_{55},$$
$$\frac{\partial u_\theta}{\partial r} = \frac{1}{r}u_\theta - \frac{1}{r}\frac{\partial u_r}{\partial \theta} + \tau_{r\theta}a_{44} + \tau_{rz}a_{45}. \tag{25}$$

All notations in (25) correspond to those given in (20). The stresses σ_{rr}^0, τ_{rz}^0 and $\tau_{r\theta}^0$ are determined after solving the problem of the precritical stress–strain state (20) based on the loading acting on the anisotropic cylindrical shell.

The solution of system (25) in the case of solving the stability problem under distributed external lateral pressure must satisfy the conditions on the lateral surfaces at $r = r_1$:

$$\sigma_{rr}^0(r_1,z,\theta) = 0, \quad \tau_{rz}^0(r_1,z,\theta) = 0, \quad \tau_{r\theta}^0(r_1,z,\theta) = 0$$

and $r = r_2$:

$$\sigma_{rr}^n(r_2,z,\theta) = -q_r^n(z), \quad \tau_{rz}^n(r_2,z,\theta) = 0, \quad \tau_{r\theta}^n(r_2,z,\theta) = 0. \tag{26}$$

The boundary conditions at the ends of the cylindrical shell at $z = 0$ and $z = L$ are assumed as follows:

$$\sigma_{zz} = u_r = u_\theta = 0. \tag{27}$$

Methodology for solving the stability problem

The stability problem was solved by reducing the three-dimensional stability equation system to a one-dimensional system. To reduce the three-dimensional problem (25) to a one-dimensional one, we use the procedure of the Bubnov–Galerkin analytical method (Yamaki, 1968/1969; Podvornyi et al., 2017; Semenyuk et al., 2019). According to this procedure, we decompose all the components of the stresses and displacements of system (25) into a double trigonometric series in the coordinate along the generatrix z so that they satisfy the boundary conditions at the ends of (27), and consider their periodicity along the circular coordinate θ:

$$\sigma_{rr}(r,z,\theta) = \sum_{m=1}^{\infty}\sum_{k=0}^{\infty}\left[y_{1,pk}(r)\cos k\theta + y'_{1,mk}(r)\sin k\theta\right]\sin l_m z,$$
$$\tau_{rz}(r,z,\theta) = \sum_{m=0}^{\infty}\sum_{k=0}^{\infty}\left[y_{2,pk}(r)\cos k\theta + y'_{2,mk}(r)\sin k\theta\right]\cos l_m z,$$
$$\tau_{r\theta}(r,z,\theta) = \sum_{m=1}^{\infty}\sum_{k=0}^{\infty}\left[y_{3,pk}(r)\sin k\theta + y'_{3,mk}(r)\cos k\theta\right]\sin l_m z,$$

$$u_r(r,z,\theta)=\sum_{m=1}^{\infty}\sum_{k=0}^{\infty}\left[y_{4,pk}(r)\cos k\theta+y'_{4,mk}(r)\sin k\theta\right]\sin l_m z,$$

$$u_z(r,z,\theta)=\sum_{m=0}^{\infty}\sum_{k=0}^{\infty}\left[y_{5,pk}(r)\cos k\theta+y'_{5,mk}(r)\sin k\theta\right]\cos l_m z,$$

$$u_\theta(r,z,\theta)=\sum_{m=1}^{\infty}\sum_{k=0}^{\infty}\left[y_{6,pk}(r)\sin k\theta+y'_{6,mk}(r)\cos k\theta\right]\sin l_m z, \tag{28}$$

where:

$y_{i,pk}$, $y'_{i,mk}$, $(i=\overline{1,6})$ – coefficients for the expansion into trigonometric Fourier series of the stress and displacement components of the shell: σ_{rr}, τ_{rz}, $\tau_{r\theta}$, u_r, u_z, u_θ,

p, m, k – wave numbers in these rows,

$l_m=\dfrac{m\pi}{L}$, where L is the length of the cylinder's base (Fig. 1).

After some mathematical transformations and separating variables in equations (25) using relations (28), we obtain an infinite system of ordinary differential stability equations in the normal Cauchy form:

$$\frac{d\overline{y}}{dr}=T(r,\lambda)\,\overline{y},\qquad T(r,\lambda)=t_{i,j}(r,\lambda),\qquad i=\overline{1,\infty},\qquad j=\overline{1,\infty}, \tag{29}$$

where:

$\overline{y}=\left\{y_{1,p};y_{2,p};y_{3,p};y_{4,p};y_{5,p};y_{6,p};y'_{1,mk};y'_{2,mk};y'_{3,mk};y'_{4,mk}\,y'_{5,mk};y'_{6,mk}\right\}^T$ – solution vector function composed of the coefficients of the double Fourier series expansion of the stress and displacement components in the axial direction z, and the circumferential coordinate θ of the shell is a solving vector function,

$T(r,\lambda)$ – square matrix with variable coefficients that depends on the argument r and load parameters λ.

The one-dimensional system of differential equations (29) is solved using the numerical method of discrete orthogonalisation. This method has been adapted to solve stability problems of anisotropic cylindrical shells (Bazhenov et al., 2010).

To determine the critical load values, the static Euler criterion is used, and the problem is solved by a step-by-step search method. In this process, an external load is specified, for which system (20) is solved. The components of the stress–strain state σ^0_{rr}, τ^0_{rz} and $\tau^0_{r\theta}$, determined from (20) using (15), are substituted into system (29), and the discriminant of the matrix of this system of equations is computed, taking into account the appropriate boundary conditions on the shell surfaces. This process is repeated with varying external load values until a so-called non-trivial solution is obtained, that is, when the discriminant of the matrix of system (29) becomes zero, which corresponds to the moment of loss of stability.

RESULTS AND DISCUSSION

The following presentation outlines the possibilities of the proposed approach. The problem of comparing the values of critical loads of an anisotropic cylindrical shell made of a pre-orthotropic fibrous material, boron plastic, with the same shell but having an outer layer of a ceramic-metallic functionally graded material, was considered. The FGM layer can be used as a protective layer for the fibrous material when exposed to high-intensity temperature fields. It is important to note that both shell structures are subject to distributed external pressure. The main directions of elasticity of the boron plastic and FGM can be rotated by an angle ψ relative to the direction of the shell (Fig. 1).

Mechanical characteristics of a unidirectional fibrous boron plastic composite are (Lubin, 2013): $E_{zz} = 280E_0$, $E_{\theta\theta} = E_{rr} = 31E_0$, $G_{z\theta} = G_{r\theta} = 10.5E_0$, $G_{rz} = 21.2E_0$, $\nu_{\theta z} = 0.25$, $E_0 = 1{,}000$ MPa.

A mixture of silicon nitride and titanium alloy with a volume fraction of mixed materials ($N = 1$) was selected as the FGM (Shen, 2009). The components of the FGM at the temperature of the initial undeformed state $t_0 = 293$ K have the following mechanical characteristics: silicon nitride: $E_c = 322.77E_0$, $\nu_c = 0.24$; titanium alloy (Ti-6Al-4V): $E_m = 106.09E_0$, $\nu_m = 0.298$.

The change in the volume fractions of silicon nitride and titanium alloy occurs with the thickness of the FGM layer. The general characteristics of the FGM are determined according to (Shen, 2009):

$$E(\xi) = (E_c - E_m)\left(\frac{\xi_f}{h_f}\right)^N + E_m, \quad \nu(\xi) = (\nu_c - \nu_m)\left(\frac{\xi_f}{h_f}\right)^N + \nu_m, \tag{30}$$

where:
$E(\xi)$, $\nu(\xi)$ – mechanical characteristics of the joint material in terms of thickness,
h_f – thickness of the functionally graded layer of the shell,
ξ_f – coordinate over the thickness of the FGM layer $\xi_f = r - r_{f1}$,
r – coordinate of the shell thickness of an arbitrary point in the general coordinate system (Fig. 1),
r_{f1} – coordinate of the inner surface of the FGM layer in the general coordinate system.

The cylindrical shell structure made of boron plastic has the following geometric parameters (Fig. 1): $L = 1.2$ m, $r_1 = 0.5925$ m, $r_2 = 0.6075$ m. The comparable boron plastic fibre composite and FGM shells have similar geometrical characteristics, but are composed of two types of materials in terms of thickness: the inner part $r_1 = 0.5925$ m, $r_{f1} = 0.6025$ m (made of boron plastic layer) and outer layer $r_{f1} = 0.6025$ m, $r_2 = 0.6075$ m (made of ceramic-metal FGM).

A study was conducted to assess the stability of cylindrical shell structures with a mid-surface radius $r_0 = 0.6$ m based on the ratio of the total thickness of the shells h based on their mid-surface radius $\frac{h}{r_0} = \frac{1}{40}$.

External lateral pressure was exerted on the shells $q = -q_0 \sin\left(\frac{\pi z}{L}\right)$. The temperature of the materials remains unchanged (293 K) and corresponds to the temperature of the initial undamaged state of the structures.

Table 1 and Figure 2 show the results of a comparison of the critical loads of the external side pressure (q^{cr}) from rotation angle (ψ) on the main directions of elasticity of the shell material. In Figure 2, Curve 1 (solid) represents the results obtained for the boron plastic design. In Figure 2, Curve 2 (dashed) characterises the two-layer structure of the shell: the inner layer is boron plastic; the outer layer is FGM.

Table 1. Critical loads (q^{cr}) for boron plastic shell and boron plastic shell with functionally graded materials (FGM) layer

Specification	Angle ψ [°]									
	0	10	20	30	40	50	60	70	80	90
q^{cr} for boron plastic shell [MPa]	2.36 (6)	2.67 (6)	3.34 (6)	4.04 (6)	4.79 (5)	5.65 (5)	6.58 (4)	7.07 (4)	7.61 (4)	7.90 (4)
q^{cr} for boron plastic shell with a layer of ceramic-metal FGM [MPa]	4.49 (5)	4.61 (5)	5.03 (5)	5.57 (5)	6.58 (5)	7.84 (5)	8.84 (5)	9.74 (5)	10.05 (4)	10.34 (4)
Difference between critical loads (Δ) [%]	90.3	72.7	50.6	37.9	37.4	38.8	34.3	37.8	32.1	30.9

Note: The circumferential wave number parameter, which corresponds to the moment of stability loss, is presented in parentheses.

Source: own work.

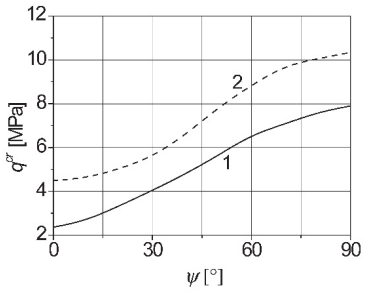


Fig. 2. Critical loads (q^{cr}) for: 1 – boron plastic shell, 2 – boron plastic shell with functionally graded materials (FGM) layer

Source: own work.

The following conclusions can be drawn based on the analysis of the results given. The use of FGM as the outer layer of a cylindrical shell structure subjected to external lateral pressure leads to an increase in critical load values over the entire range of variation of the rotation angle of the principal material directions. The greatest difference between the compared values reaches 90.3% and occurs at $\psi = 0°$. With the increasing angle ψ, the difference between the compared results decreases and is 30.9% at $\psi = 90°$. To explain this effect, in the case of distributed lateral pressure, it is possible to increase the modulus of elasticity of the fibrous material of the boron plastic in the circular direction with an increase in angle ψ in the range from 0° to 90°. It is also noted that the results presented in Figure 2 and Table 1 indicate that even in the absence of a temperature effect on the shell, the use of FGM as the outer layer of the cylindrical shell structure leads to an increase in its bearing capacity, in terms of stability.

Considering the results presented in Table 1 and Figure 2, the problem of determining the critical loads of an anisotropic cylindrical shell made of a different number of layers of fibrous boron plastic material with an outer layer of ceramic-metal functionally graded material, which is under the influence of distributed external pressure, was considered.

The study of critical loads of the anisotropic cylindrical shell was carried out considering the increase in the number of cross-reinforced layers of boron plastic and the change in angle $\pm\psi$. The range of their laying position is from 0° to 90°. The results of an orthotropic approach to the calculation of such a shell are also presented, considering that the mechanical characteristics c_{16}, c_{26}, c_{36}, a_{45} in the generalised Hooke law (Lekhnitskii, 1981; Semenyuk et al., 2023) are assumed to have zero values.

Table 2 and Figure 3 show the results of the study of the dependence of the critical values of the external side pressure q^{cr} on the rotation angle $\pm\psi$ with respect to the main directions of elasticity of the fibrous composite. In Figure 3, Curve 1 (continuous) represents the results obtained for a structure where the boron plastic layer of the shell is laid at an angle ψ. In Figure 3, Curve 2 (dashed) characterises a two-layer boron plastic structure, where the same thickness layers are cross-reinforced at an angle $\pm\psi$. In Figure 3, Curve 3 (dashed) and Curve 4 (bar-dashed) characterise, respectively, the three-layer and four-layer structure of the boron plastic component of the shell material, where the layers are also cross-reinforced at angles $\pm\psi$. In Figure 3, Curve 1′ presents the results of the orthotropic approach to calculating such a shell structure.

Table 2. Critical loads (q^{cr}) of layered boron plastic shell with functionally graded materials (FGM) layer

Specification	Angle $\pm\psi$ [°]									
	0	10	20	30	40	50	60	70	80	90
q^{cr} for single-layer boron plastic [MPa]	4.63 (5)	4.85 (5)	5.29 (5)	5.93 (5)	6.98 (5)	8.25 (5)	9.31 (5)	10.25 (5)	10.58 (4)	10.66 (4)
q^{cr} for two-layer boron plastic [MPa]	4.63 (5)	4.93 (5)	5.34 (5)	5.67 (5)	6.61 (5)	8.21 (5)	9.80 (5)	10.86 (5)	10.85 (4)	10.66 (4)
q^{cr} for three-layer boron plastic [MPa]	4.63 (5)	4.94 (5)	5.37 (5)	5.77 (5)	6.81 (5)	8.54 (5)	10.26 (5)	11.25 (4)	10.97 (4)	10.66 (4)
q^{cr} for four-layer boron plastic [MPa]	4.63 (5)	4.94 (5)	5.36 (5)	5.73 (5)	6.75 (5)	8.51 (5)	10.26 (5)	11.25 (4)	10.98 (4)	10.66 (4)
q^{cr} for eight-layer boron plastic [MPa]	4.63 (5)	4.94 (5)	5.37 (5)	5.75 (5)	6.79 (5)	8.58 (5)	10.35 (5)	11.30 (4)	11.00 (4)	10.66 (4)
Orthotropic approach	4.63 (5)	4.94 (5)	5.37 (5)	5.75 (5)	6.80 (5)	8.61 (5)	10.41 (5)	11.34 (4)	11.02 (4)	10.66 (4)

Note: The circumferential wave number parameter, which corresponds to the moment of stability loss, is presented in parentheses.

Source: own work.

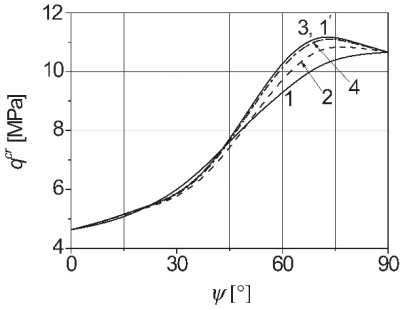


Fig. 3. Critical loads (q^{cr}) of layered boron plastic shell with functionally graded materials (FGM) layer

Source: own work.

From the analysis of the results shown in Figure 3, when the angle of rotation of the main directions of elasticity of the fibrous composite changes, the critical values of the shell with the FGM layer change. For the single-layer structure of a boron plastic component, an angle increase ψ from 0° to 90° leads to a continuous increase in the critical values of the external side pressure q^{cr}. The increase in critical loads on the change of the reinforcement angle (ψ) from 0° to 90° reaches 230%. A local maximum of critical values forms when the number of cross-reinforced layers in the fibrous component of the shell is increased: q^{cr} in the range $60° \leq \pm\psi \leq 70°$. This effect, shown in Figure 2, is most pronounced for the three-layer boron plastic structure (Curve 3), where q^{cr} exceeds the value determined at $\psi = 90°$ by 5.5%. The presented results also show that increasing the number of boron plastic layers from a single to two, in the range of rotation angle $30° \leq \pm\psi \leq 50°$, leads to a decrease in the critical values q^{cr}, with the discrepancy reaching up to 4.5%; in other ranges of $\pm\psi$, the values of q^{cr} are higher for the two-layer configuration. A further increase in the number of layers of the boron plastic package leads to the critical loads q^{cr} approaching the orthotropic approach obtained in the calculation of the structure. It should be noted that in the eight cross-reinforced layers, the discrepancy between the critical loads obtained, considering the mechanical characteristics c_{16}, c_{26}, c_{36}, and a_{45} of the generalised Hook law and without them, becomes less than 1%, so the corresponding curves in Figure 3 are not included.

CONCLUSIONS

The article presents a three-dimensional system of differential equations describing the stability of a cylindrical anisotropic shell structure, based on the Hu–Washizu variational principle. The system is reduced to a one-dimensional one by using expansions in a double trigonometric Fourier series. The approximation of the unknowns along the generative and circumferential directions of the shell structure is then carried out using the Bubnov–Galerkin analytical method. The numerical method of discrete orthogonalization is then used to solve the resulting one-dimensional system of differential equations.

The proposed approach facilitates the resolution of stability concerns inherent in the fabrication of layered shell structures utilising contemporary composite materials in a three-dimensional formulation.

A comparison of the values of critical loads of external lateral pressure for an anisotropic cylindrical shell made of fibrous composite and the same one with a layer of functionally graded material is carried out. The findings reveal that incorporating an FGM layer enhances the critical loads of the structure. The critical values of the external lateral pressure for a layered anisotropic cylindrical shell constructed from a fibrous composite with an outer layer of a functionally graded material are investigated. The investigation further involves the analysis of the critical loads in relation to the angle of rotation of the primary elastic directions of the unidirectional fibrous material, as well as the number of its layers.

REFERENCES

Abovsky, N. P., Andreev, N. P. & Deruga, A. P. (1978). *Variatsionnyye printsipy teorii uprugosti i teorii obolochek*. Moskva: Nauka.

Ambartsumyan, S. A. (1974). *Obshchaya teoriya anizotropnykh obolochek*. Moskva: Nauka.

Bazhenov, V. A., Kryvenko, O. P. & Solovey, M. O. (2010). *Neliniyne deformuvannya ta stiykist' pruzhnykh obolonok neodnoridnoyi struktury*. Kyiv: Vipol.

Bazhenov, V. A., Semenyuk, M. P. & Trach, V. M. (2010). *Neliniyne deformuvannya, stiykist' i zakrytychna povedinka anizotropnykh obolonok*. Kyiv: Karavela.

Grigorenko, Ya. M. & Kryukov, N. N. (1988). *Chislennyye resheniya zadach statiki gibkikh sloistykh obolochek s peremennymi parametrami.* Kyiv: Naukova Duma.

Guz, A. N. (1986). *Osnovy trekhmernoy teorii ustoychivosti deformiruyemykh tel*. Kyiv: Vishchashkola.

Guz, A. N. & Babich, I. Yu. (1980). *Trekhmernaya teoriya ustoychivosti sterzhney, plastin i obolochek*. Kyiv: Vishchashkola.

Guz, A. N. & Babich, I. Yu. (1985). *Prostranstvennyye zadachi teorii uprugosti i plastichnosti.* Vol. 4. *Trekhmernaya teoriya ustoychivosti deformiruyemykh tel*. Kyiv: Naukova Duma.

Kołakowski, Z. & Mania, R. (2012). Semi-analytical method versus the FEM for analysis of the local post-buckling of thin-walled composite structures. *Composite Structures*, *97*, 99–106. https://doi.org/10.1016/j.compstruct.2012.10.035

Kowal-Michalska, K. & Mania, R. (2013). Static and Dynamic Thermomechanical Buckling Loads of Functionally Graded Plates. *Mechanics and Mechanical Engineering*, *17* (1), 99–112.

Kryvenko, O. P., Lizunov, P. P., Vorona, Y. V. & Kalashnikov, O. B. (2024). Modeling of Nonlinear Deformation, Buckling, and Vibration Processes of Elastic Shells in Inhomogeneous Structure. *International Applied Mechanics*, *60* (4), 464–478. https://doi.org/10.1007/s10778-024-01298-2

Lanczos, C. (1986). *The Variational Principles of Mechanics* (Dover Books on Physics). Dover Publications.

Lee, Y., Zhao, X. & Reddy, J. N. (2010). Postbuckling analysis of functionally graded plates subject to compressive and thermal loads. *Computer Methods in Applied Mechanics and Engineering*, *199* (25–28), 1645–1653. https://doi.org/10.1016/j.cma.2010.01.008

Lekhnitskii, S. G. (1981). *Theory of Elasticity of an Anisotropic Body*. Dagenham: Central Books.

Lubin, G. (2013). *Handbook of Composites*. Springer Science & Business Media.

Novozhilov, V. V. (1961). *Theory of elasticity* [translated to English by J. L. Lusher]. Elsevier.

Podvornyi, A. V., Semenyuk, N. P. & Trach, V. M. (2017). Stability of Inhomogeneous Cylindrical Shell under Distributed External Pressure in the Spatial Statement. *International Applied Mechanics*, *53* (6), 623–638. https://doi.org/10.1007/s10778-018-0845-7

Reddy, J. N. (2000). Analysis of functionally graded plates. *International Journal for Numerical Methods in Engineering*, *47* (1), 663–684. https://doi.org/10.1002/(SICI)1097-0207(20000110/30)47:1/33.0.CO;2-8

Semenyuk, N. P., Trach, V. M. & Podvornyi, A. V. (2019). Spatial Stability of Layered Anisotropic Cylindrical Shells Under Compressive Loads. *International Applied Mechanics*, *55* (2), 211–221. https://doi.org/10.1007/s10778-019-00951-5

Semenyuk, N. P., Trach, V. M. & Podvornyi, A. V. (2023). Stress–strain state of a thick-walled anisotropic cylindrical shell. *International Applied Mechanics*, *59* (1), 79–89. https://doi.org/10.1007/s10778-023-01201-5

Shen, H-S. (2009). *Functionally graded materials: nonlinear analysis of plates and shells*. Boca Raton–London–New York: CRC Press Taylor & Francis Group.

Tonti, E. (1967). Variational principles in elastostatics. *Meccanica*, *2*, 201–208. https://doi.org/10.1007/BF02153074

Trach, V. M., Podvorny, A. V. & Khoruzhiy, M. M. (2019). *Deformuvannya ta stiykist' netonkykh anizotropnykh obolonok.* Kyiv: Karavela.

Trach, V. M., Podvorny, A. V. & Zhukova, N. B. (2023). Stiykist' netonkykh anizotropnykh tsylindrychnykh obolonok v prostoroviy postanovtsi pid rozpodilenym bokovym tyskom [Stability of non-thin anisotropic cylindrical shells in a spatial setting under distributed lateral pressure]. *Bulletin of the Taras Shevchenko National University of Kyiv, Series Physical and Mathematical Sciences*, *2*, 152–155. https://doi.org/10.17721/1812-5409.2023/2

Trach, V., Semenuk, M. & Podvornyi, A. (2016). Stability of anisotropic cylindrical shells in three-dimensional state under axial compression. *Acta Scientiarum Polonorum. Architectura*, *15* (4), 169–183.

Washizu, K. (1982). *Variational Methods in Elasticity and Plasticity*. Pergamon Press.

Yamaki, N. (1968/1969). Buckling of Circular Cylindrical Shells under External Pressure. *Reports of the Institute of High Speed Mechanics, Thoku University*, *20*, 35–55.

Zienkiewicz, O. C. (1972). *Metoda elementów skończonych*. Warszawa: Arkady.

ZASADA WARIACYJNA HU–WASHIZU W ZADANIACH STATECZNOŚCI NIECIENKICH ANIZOTROPOWYCH POWŁOK CYLINDRYCZNYCH Z NOWOCZESNYCH MATERIAŁÓW KOMPOZYTOWYCH W UJĘCIU PRZESTRZENNYM

STRESZCZENIE

Z wykorzystaniem zasady wariacyjnej Hu–Washizu otrzymano trójwymiarowy układ równań różniczkowych cząstkowych teorii sprężystości ciała anizotropowego, zapisany w cylindrycznym układzie współrzędnych. Aby sprowadzić go do postaci jednowymiarowej, zastosowano analityczną metodę Bubnowa–Galerkina. Rozwiązanie jednowymiarowego zadania w kierunku normalnym do powierzchni środkowej konstrukcji powłokowej przeprowadzono przy użyciu numerycznej metody dyskretnej ortogonalizacji. Przeprowadzono badania wartości krytycznych obciążeń zewnętrznego ciśnienia bocznego dla anizotropowej powłoki cylindrycznej z kompozytu włóknistego oraz takiej samej powłoki z dodatkową warstwą materiału funkcjonalnie gradientowego (FGM). Przeanalizowano zależność wartości krytycznych obciążeń od kąta obrotu głównych kierunków sprężystości materiału jednokierunkowego oraz liczby jego warstw. Wykazano, że zastosowanie warstwy FGM pozwala na zwiększenie wartości krytycznych obciążeń konstrukcji.

Słowa kluczowe: anizotropowa powłoka warstwowa, kompozyt włóknisty, materiał funkcjonalnie gradientowy, obciążenie krytyczne, ujęcie przestrzenne

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ZEN TEMPLE ARCHITECTURE AND SUSTAINABILITY: EXAMINING TRADITIONAL DESIGNS AND CONTEMPORARY ADAPTATIONS IN JAPAN

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ABSTRACT

Zen Buddhism originated in China and profoundly influenced Japanese architecture. To this day, *Zen no Kenchiku* [English: *Zen architecture*] by Hideo Yokoyama is considered the most authoritative publication on the elements of Japanese Zen architecture. However, contemporary Zen temples have undergone numerous reconstructions and modifications, raising the question of how closely their current forms adhere to the original designs. This study aims to compare the contemporary architecture of selected Zen temples with the architectural features recognised as fundamental to the Zen style in the 1960s. The temples were chosen based on their historical and contemporary significance, with a focus on the Rinzai and Sōtō schools. We reviewed the architectural elements described in *Zen no Kenchiku* and supplemented them with information from other sources and secondary literature. Our analysis revealed that none of the temples we examined contained all of the Zen architectural elements identified by Yokoyama. As demonstrated, Zen architecture is evolving and may contribute to sustainable building practices. These findings lay the groundwork for further research on Zen temples, particularly in the context of sustainable architecture.

Keywords: Japanese architecture, natural material, sustainability, Zen Buddhism

INTRODUCTION

Renowned for its simplicity and austerity, Zen Buddhism is one of the most significant Buddhist traditions in Japan (Nagatomo, 2006). Zen temples in Japan reflect religious doctrine as well as centuries of cultural, aesthetic, and technological adaptation. Influenced by Chinese Chan, Zen architecture developed its own identity in Japan, guided by principles of simplicity, functionality, and spiritual symbolism. These forms embody religious values, with spatial organisation and material choices serving ritualistic, meditative, and didactic purposes.

Given Zen Buddhism's historical impact and architectural legacy, this study examines how contemporary Zen temple design reflects or diverges from traditional, religiously grounded architectural principles.

This study aims to analyse how selected contemporary Zen temples from the Rinzai and Sōtō schools retain, reinterpret, or abandon traditional architectural features associated with Zen design. The study poses two key research questions to guide the analysis: (i) To what extent do selected contemporary Zen temples conform to the characteristics outlined by Yokoyama? This question assesses the continuity and transformation

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of Zen architectural forms from the 1960s to the present. The study also examines differences in architectural features between modern and historical temples, as well as how interpretation or adherence to specific elements varies between the Rinzai and Sōtō schools. The second question is (ii): Can the architectural features identified in this study reliably indicate a temple's adherence to the Zen architectural style in the contemporary context?

By addressing these questions, the study contributes to a deeper understanding of how religious values are expressed architecturally in a contemporary context. Additionally, it explores how tradition can be reconciled with innovation in sustainable and culturally respectful design.

LITERATURE REVIEW

Origins of Zen and its architecture in Japan

Zen, originating in India, spread to China in the 6th century, where it became known as Chan. The Chan Buddhist tradition in China evolved over several centuries before it was introduced to Japan by Japanese monks during the Kamakura period (1185–1333). The Zen style that Japan adopted was that of the Southern Song Dynasty (1127–1279). In replicating this tradition, Japanese monks sought to preserve both the practice and the environment in which Zen was practised, including the architecture. Initially, Japanese Zen architecture closely followed Chinese models, with notable Chan temples serving as key influences on the design of Japanese Zen temples. Japanese craftsmen, having studied these structures in China, brought back detailed blueprints and knowledge, including the expertise of Chinese artisans skilled in Chan temple construction (Ku, 2016).

Over time, however, Zen architecture in Japan began to evolve, reflecting the Buddhist emphasis on simplicity and austerity. This simplicity, a characteristic of Zen, gradually became more pronounced in certain elements of Zen buildings, resulting in a shift that altered the strict minimalism originally intended (Sun, 2025).

Zen style, known as *kara-yō* (Chinese style) in Japanese (Bodiford, 2025), was introduced alongside Indian architectural influences. While the Indian style did not persist long in Japan, eventually merging into the broader Japanese style, Zen architecture became a dominant influence, especially during Japan's medieval period. It maintained a distinct identity, coexisting with the traditional Japanese architectural style, leading to the development of hybrid styles, such as the eclectic *sechūjō* style, which merged Zen and Japanese elements (Young & Young, 2019).

The Rinzai school

The Rinzai school is one of the two main branches of Zen Buddhism in Japan, introduced by Eisai (1141–1215 AD) during the Kamakura period. Having previously studied Tendai Buddhism, Eisai brought Rinzai teachings from China, where they were initially mingled with elements of Shingon and Tendai traditions. The Rinzai school became particularly favoured by the ruling classes in Japan, who provided substantial financial support. The core of Rinzai practice emphasises sudden enlightenment, with meditation on koans playing a central role in achieving this realisation. Unlike the Sōtō school, which has a centralised temple system, Rinzai is organised into a network of 15 branches, each with its own central temple. Major temples in this network include Nanzen-ji, Tōfuku-ji, and Kennin-ji. During the medieval period, the Rinzai school operated under a hierarchical system called *gozan*, which classified temples into three categories based on their influence and importance (Dumoulin, 2005; Welter, 2006).

Gozan system

The *gozan* system, active from the early 14th century until the Ōnin War (1467–1477), played a significant role in organising Zen temples in Japan. Derived from the Chinese Chan model, the system initially involved five major temples known as *gozan*, with these temples situated at the top of the hierarchy. The *gozan* system extended to include hundreds of temples, each governed by a hierarchy that reflected the political preferences

of the ruling shogunate. These temples not only provided spiritual guidance but also influenced Japanese society and culture, with some maintaining their prominent status into the modern era (Goble, 2007; Kage, 2022).

The Sōtō school

The Sōtō school is the largest Zen school in Japan, founded by Dōgen (1200–1253 AD) during the Kamakura period. Dōgen, initially a Tendai monk, travelled to China to study Chan Zen, later returning to Japan to spread these teachings. Dōgen's disciple, Keizan (1268–1325 AD), is also considered a co-founder due to his role in expanding the Sōtō school during the 13th and 14th centuries. Unlike Rinzai, Sōtō Zen focused on meditation in a seated posture (*zazen*) as a means of achieving enlightenment, and its teachings became particularly popular among rural populations in Japan. Sōtō Zen is represented by two main temples, Eihei-ji, founded by Dōgen, and Sōji-ji, founded by Keizan. The school expanded significantly during the medieval period, gaining followers not only among common people but also among the local aristocracy. The Sōtō school's approach to Zen practice has gained worldwide recognition, contributing to its influence across the globe (Heine, 2021; Kase, Choi & Nonaka, 2022; Masaki, 2022).

Zen architectural style

The Zen architectural style, influenced by Chan temple architecture, is characterised by specific features that distinguish it from other architectural traditions in Japan. These include the arrangement of the temple complex, unique types of beams and columns, and other structural elements. This section discusses key aspects of Zen architecture, particularly the layout of buildings within the *shichidō garan* (temple complex of seven halls), a central concept in Zen Buddhist temple design (Heine, 2023).

Temple complex layout: shichidō garan

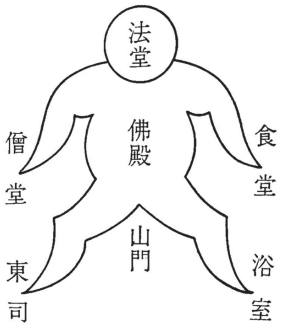
Shichidō garan, meaning "temple complex of seven halls", refers to a specific number and arrangement of main buildings within Zen Buddhist temples. Although the total number of buildings in a temple complex is typically higher, the core buildings, which form the essence of the Zen temple, remain constant (Borup, 2008). This concept, derived from Chan temples during the Southern Song period, was adapted by Zen Buddhism. The term *shichidō garan* was not initially used in Japan for Zen complexes but was instead applied to temples from the Nara period (710–784 AD). The layout of these temples differed from the Zen style, both in the composition of the halls and their positioning within the complex. Zen architecture is marked by a strict arrangement of temple buildings, which is evident in earlier Buddhist architecture from the Nara period. In contrast, the Tendai and Shingon schools of the Heian period (794–1185 AD) had more flexible layouts (Faulkes, 1994). Zen architecture, while returning to earlier traditions, established its own set of rules (Lomas et al., 2017). According to Helmut Brinker, a specialist in Zen art and architectural history, the standardisation of the Zen *shichidō garan* in Japan did not occur until the 15th century (Heine, 2015). Variations of the *shichidō garan* layout existed in earlier centuries, as the precise form was not yet fully established (Heine, 2023).

The *shichidō garan* layout places important buildings for Zen practice along the north–south axis, while less significant daily-use structures are positioned along the east–west axis. This layout, first used in Chan temples during the Southern Song period, distinguishes Zen architecture from earlier Buddhist styles (Stavros, 2017).

Throughout history, the layout of Buddhist temple complexes has varied significantly. One example of this variation is the placement of pagodas (Xie, 2024). In earlier periods, pagodas were located along the central axis with the most important buildings. During the Nara period, considered the "Golden Age of Buddhist Architecture" (Sadler, 2011), two pagodas were typically positioned symmetrically, one to the east and one to the west (Xie, 2024). However, in Zen architecture, the significance of pagodas is greatly reduced. Instead, buildings intended for everyday use, such as latrines and washrooms, often occupy these positions. This shift reflects the contrast between formerly sacred spatial arrangements and spaces now designated for worldly concerns and purification (Heine, 2011; Sadler, 2011).

Anthropomorphic significance of the building layout

The arrangement of buildings in Zen Buddhist complexes, particularly in the *shichidō garan,* is believed to carry anthropomorphic symbolism, representing different parts of the human body (Fig. 1). This feature distinguishes Zen *shichidō garan* from the Nara period interpretation of the term. Yokoyama (1967) presents a schematic where specific halls are associated with body parts: the mountain gate (*sanmon*) represents the crotch, the Buddha hall (*butsuden*) represents the heart, the Dharma hall (*hattō*) represents the head, the latrines and washrooms represent the feet, and the monk's hall (*sōdō*) and dining hall (*shokudō*) represent the hands. This anthropomorphic association, however, was likely introduced during the Edo period (1603–1868), despite the *shichidō garan* layout being used since the Kamakura period. Initially, this symbolic correspondence was likely a mnemonic tool for artisans during construction, rather than a core aspect of Zen teachings.



第１図　七堂人体表相図

Fig. 1. Anthropomorphic analogy of *shichidō garan*

Source: Yokoyama (1967).

Collcutt (1981) asserts that while Zen temples adhered to a building layout derived from Chan temples, neither the term *shichidō garan* nor the anthropomorphic analogy was used in Chinese Chan temples. Therefore, these innovations – both the use of the term *shichidō garan* and the anthropomorphic analogy – are unique to Japan. Had these Japanese rules been applied to Chan temples, the layout would have been similar, with slight variations. Chinese Chan temples, serving as models for Japanese Zen temples, were larger and more flexible due to their gradual development. For example, the placement of latrines in Chinese Chan temples was more pragmatic, while in Japanese Zen temples, the positions were fixed. This difference can be attributed to the fact that Chan Buddhism in China evolved over many centuries, while in Japan, it was adopted in a more standardised form.

An interesting exception to the strict layout is the Sōji-ji temple, closely associated with the well-planned Eihei-ji temple. Despite its non-compliant layout, the term *shichidō garan* is still applied to Sōji-ji, suggesting that the defining characteristic of a *shichidō garan* temple is simply the inclusion of seven main buildings, as argued by Winfield (2015).

Foundations of Zen temples

The foundations of Zen temples are often constructed with stone masonry, typically categorised into two types: *kiri-ishizumi* and *ransekizumi* (Yokoyama, 1967). *Kiri-ishizumi* refers to foundations using precisely cut stone (Fig. 2), while *ransekizumi* consists of irregularly shaped, uncut stones stacked randomly. The spaces between the larger stones are filled with smaller pebbles, ensuring structural stability. This distinction in masonry techniques contributes to the overall aesthetic and functional characteristics of Zen temple foundations.



Fig. 2. *Kiri-ishizumi* masonry: precisely cut stone foundation used in Zen temples

Source: photo by Natálie Dobrovolná 2024.

Floors of Zen temples: diagonal tiling as a traditional element

The floors of Zen temples, both internally and externally, are typically not made of wood. Instead, they are constructed from compressed earth, plaster, or, most commonly, paved with square stone tiles (Caname Jisha Co., 2017b). These tiles are laid at a 45° angle to the building's sides, a traditional practice known as *shihanjiki*, which is translated here as diagonal tiling (Fig. 3). This unique flooring design contributes to the distinct aesthetic of Zen temple architecture.



Fig. 3. Diagonal tiling (*shihanjiki*) in Zen temples, using square stone tiles laid at a 45° angle

Source: photo by Natálie Dobrovolná 2024.

Columns and their appearance in Zen temples

Columns in Zen temples are typically round, with rounded ends, and are referred to as *chimaki*, named after a rice dumpling that resembles their shape. According to Young and Young (2019), Zen temples are also characterised by square columns, which are thinner compared to earlier architectural styles. They are often painted in traditional Japanese vermilion. *Chimaki* columns are a distinctive feature of Zen architecture, as noted by Yokoyama (1967), and differ from those used in other Japanese architectural styles. The base of a column, called *soban* (or *sōban*), is placed between the column and the foundation stone. This base may be carved from stone or wood, with a concave upper part and a convex bottom.

Despite the typical prevalence of diagonal tiling and the *soban* base in Zen architecture (Fig. 4), Yokoyama (1967) also mentions rare cases where Zen temples, influenced by Japanese architectural styles, feature wooden floors rather than tiled ones, and consequently, the *soban* base is absent.



Fig. 4. Column base placed on a foundation stone (*soban*) – a characteristic feature of Zen temple architecture

Source: photo by Natálie Dobrovolná 2024.

Shrimp-shaped beam trusses as a typical element

Various types of beams, varying in size, shape, and ornamentation, are employed in temple construction. A characteristic beam in Zen temple architecture is the lobster or shrimp-shaped beam (*ebi koryō*) (Lin, 2017). This beam is named after its shape, which resembles the curvature of a shrimp's body, achieving two heights (Fig. 5). It is used where two points at different elevations need to be connected, and standard beams would be ineffective. Initially, the curvature of the beam was relatively subtle, but over time, as with other architectural elements, it became more pronounced. Although the shrimp-shaped beam is typical of Zen architecture and was first used in this style, it was later adopted by broader Japanese architectural traditions.

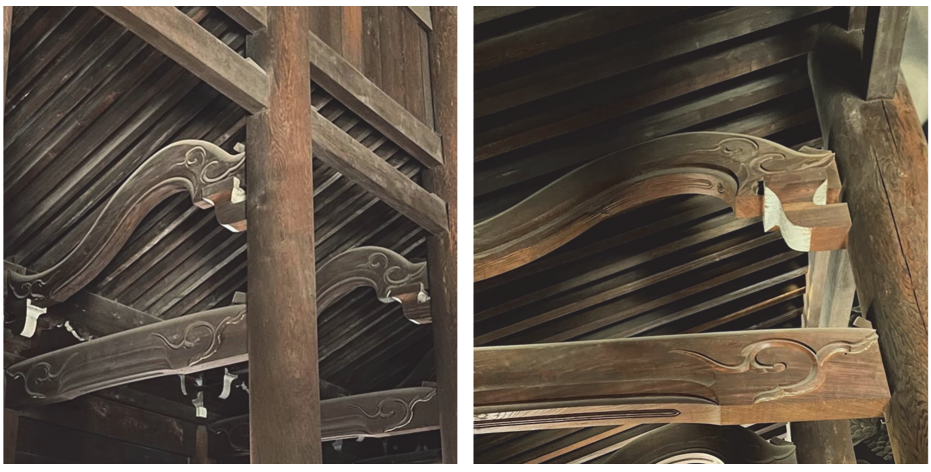


Fig. 5. Shrimp-shaped beam (*ebi koryō*) – a distinctive curved beam used in Zen temple architecture to connect different levels

Source: photos by Natálie Dobrovolná 2024.

Brackets and their use in Zen architecture

Brackets are structural elements protruding from walls designed to support roofs. Over time, as Buddhism influenced Japan, the design and complexity of brackets evolved. Zen-style brackets differ from those in Japanese and Indian styles primarily in their placement. In Japanese and Indian architecture, brackets are positioned solely on columns, while in Zen architecture, they are also placed in the spaces between the columns. Compared to earlier architectural styles, Zen brackets are more intricate, as it became customary to fill all the available space between the brackets positioned on the columns. This creates the illusion of a continuous element. This type of bracket is known as *tsumegumi* (bracket complexes). In contrast, other styles, such as Japanese, use short posts between beams for additional roof support, which developed into several variations over time.

In Zen architecture, due to the dense placement of brackets, there is minimal open space under the roof (Fig. 6). As a result, the ornamental element known as *shirin* (non-structural transition between the beams, traditionally used in other styles to fill this space) is typically absent in Zen temples. However, some sources in the Japanese Architecture and Art Net Users System (JAANUS) database argue that in Zen architecture, this element became more elaborate over time.

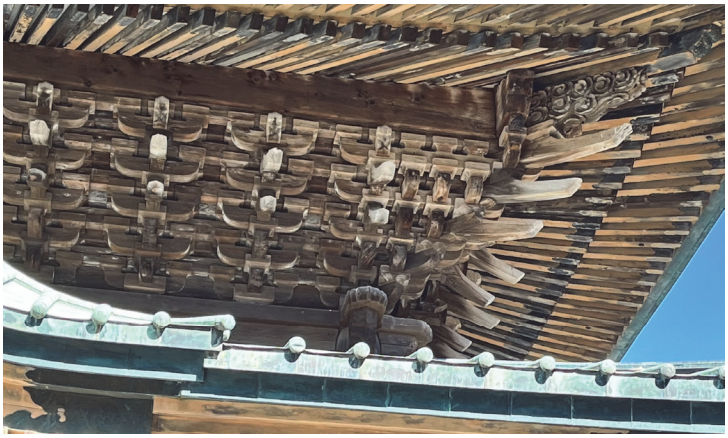


Fig. 6. Continuous brackets (*tsumegumi*) in Zen architecture create a dense, continuous structural support under the roof

Source: photo by Natálie Dobrovolná 2024.

Roofs in Zen architecture

One characteristic feature of Zen roof design is the use of rafters (*jidaruki*). These long wooden beams are placed at an angle, descending from the ridge and extending outward from the roof structure. Rafters are exposed under the eaves. They play a structural role as well as an aesthetic one. However, the second level of rafters is called *hien daruki* – these are flying rafters usually playing an aesthetic role while covering the roof structure above. Zen architecture utilises two types of rafter arrangements. The first type, parallel rafters, is also used in Japanese architecture and is easier to install. The second type, fan-shaped rafters, are more complex to install but provide the advantage of supporting the roof even at the corners, unlike parallel rafters (Fig. 7). The installation of fan-shaped rafters involves a uniform, radiating arrangement, with all rafters pointing outward from a central point at the building's centre, creating a fan-like shape. Fan-shaped rafters are typically used in multi-storey buildings under the roof of the second floor, while parallel rafters are installed on the first floor, and this rule applies even in the case of two-storey buildings (Discoe & Quinn, 2008; Lin, 2017).



Fig. 7. Parallel rafters (left) and fan-shaped rafters (right) in Zen architecture

Source: photos by Natálie Dobrovolná 2024.

According to Collcutt (1981), the mountain gates of Zen temples have two real floors, which distinguishes them from other buildings in the Zen style that typically feature smaller roofs called *mokoshi*, which only give the illusion of an additional floor. He further notes that these gates have tile roofs. Collcutt (1981) refers to *mokoshi* when mentioning that all preserved Dharma halls appear to have two floors from the outside, but in reality, they only have one. Young and Young (2019) also mention that most Zen buildings use *mokoshi* under the upper roof, which is a combination of gabled and hipped roof styles, referred to in Japanese as *irimoya*.

Ceilings in Zen temples

Ceilings in Zen architecture are typically simple, consisting of continuous smooth surfaces made from interlocking wooden planks. Unlike other architectural styles, which may feature more complex ceilings with decorative slats to support the ceiling panels, Zen ceilings are left minimalist. In buildings featuring *mokoshi*, there is typically no ceiling (Discoe & Quinn, 2008). In the vast majority of Zen buildings, ceilings maintain a plain appearance, preserving the natural wooden texture. In rare instances, however, a ceiling may feature a traditional ink painting, depicting a dragon in the clouds (*unryū*), applied using ink wash techniques (Fig. 8).



Fig. 8. Traditional ink painting of a dragon in the clouds on a mirrored ceiling, a rare decorative feature in Zen architecture

Source: photos by Natálie Dobrovolná 2024.

Windows and doors in Zen architecture

A prominent feature of Zen architecture is the *katōmado* windows, which are easily recognisable and often associated with flower-shaped or lantern-like designs. These wooden windows, exhibiting clear influences from Indian architecture, reflect the roots of Zen architecture in India. Initially, the bell-shaped curve at the top of the windows was subtle, but over time, the design expanded, and the windows became broader, deviating from the initial minimalist style of Zen architecture. The windows are made of wood with a lattice grid of thin wooden slats and are fitted with *akari shōji*, a type of *shōji* that allows light to pass through thanks to translucent Japanese paper covering (*washi*) (Discoe & Quinn, 2008; Fig. 9).



Fig. 9. *Katōmado* – distinctive wooden windows in Zen architecture, influenced by Indian design, featuring a bell-shaped curve and lattice grid with paper-covered *shōji* panels

Source: photos by Natálie Dobrovolná 2024.

In Zen architecture, panel doors, known as *sankarado* or *sangarado*, consist of planks arranged horizontally and vertically, with wooden panels inserted between them. The upper parts of these panels are often replaced with lattices or decorative carvings. The door hinges are mounted on large, ornamental wooden projections called *waraza*. Additionally, the space above the door is often filled with wavy wooden slats, a feature referred to as *namigata renji* or *tatewaki renji* (Discoe & Quinn, 2008; Fig. 10).



Fig. 10. Panel doors in Zen architecture, featuring lattice work, ornamental *waraza* projections, and wavy *namigata renji* slats above the door

Source: photos by Natálie Dobrovolná 2024.

Decoration and the influence of Zen minimalism

The natural appearance of wood is typically preserved, with little emphasis on ornamental hardware. One of the few exceptions is the use of coloured paint on the cut ends of wooden construction elements (Fig. 11). Occasionally, more elaborate details can be found in the interior, most notably in the form of dragon paintings on mirrored ceilings. However, Winfield and Heine suggest that this element likely arose from the influence of Japanese architectural styles blending with Zen aesthetics (Winfield & Heine, 2017).



Fig. 11. Minimalist decoration in Zen architecture, featuring coloured paint on wooden construction elements (left) and *kibana* protrusions at the ends of beams (right)

Source: photos by Natálie Dobrovolná 2024.

Kibana are decorative wooden protrusions typically found at the ends of beams or on consoles (Fig. 11). Various architectural styles exhibit different levels of intricacy in their carvings. Initially absent in Japanese architecture, these protrusions were introduced with the Zen style. In contrast, Indian architecture was known for its highly detailed carvings, often depicting animal motifs such as elephants. The Zen style occupies a middle

ground, with relatively understated protrusions and minimalist carvings resembling plants, clouds, or spirals. The carvings on their sides are known as *uzumaki* (spiral forms) and *karakusa* (repeating plant-like spiral motifs). A variation of *kibana*, which protrudes and resembles a fist, is referred to as *kobushibana* (Winfield & Heine, 2017).

MATERIAL AND METHODS

Study subject

This study investigates the architecture of Zen temples belonging to the Rinzai and Sōtō schools, which are the most influential Zen traditions in Japan. Temples were selected based on their historical significance, architectural importance, and their continued relevance in modern Zen practice. For the Rinzai school, three temples in Kyoto – Kennin-ji, Nanzen-ji, and Rokuon-ji – were selected. Kennin-ji, founded by the monk Eisai, is the oldest Zen temple in Japan and plays a central role in the *gozan* system. Nanzen-ji was the highest-ranked temple in the *gozan* system, a position it continues to hold. Rokuon-ji, famous for its Kinkaku-ji (Golden Pavilion), is a modern representative, rebuilt after a fire in 1950, and remains one of Japan's most iconic Zen architectural landmarks.

For the Sōtō school, two temples were selected: Eihei-ji, founded by Dōgen in 1244, and Sōji-ji, founded by Keizan in 1322. Eihei-ji represents the historical architecture of the Sōtō school, while Sōji-ji reflects the modern phase after Keizan's reforms. The original Sōji-ji complex was destroyed by fire in the late 19th century and rebuilt in the early 20th century, resulting in a complex approximately 100 years old.

The study primarily focuses on the contemporary architecture of these temples, given the lack of accessible records detailing their original designs. Scientific documentation and personal archives were used to compare the current state of the temples. Although this study does not aim for a comprehensive analysis of Zen architecture, it provides a foundational framework for future research on Zen temples, particularly in the context of sustainable architectural practices. Zen temple architecture, with its use of natural materials, minimalist design principles, and environmental integration, can serve as a model for contemporary sustainable building practices.

Justification for temple selection

Due to the complexity and variety of Zen temple complexes, this study focuses on the architecture of the seven main halls (*shichidō garan*) that are central to Zen practice. Other functional buildings, such as kitchens, dining halls, and latrines, were excluded due to their under-documentation or limited public access. The study expects to find architectural differences between the Sōtō and Rinzai schools, reflecting their distinct approaches to Zen practice. For example, Collcutt (1981) observes that the Rinzai school emphasises *kōan* practice, leading to the replacement of the monk's dormitory (*shuryō*) in favour of the Zen hall (*zendō*).

Table 1 presents the selection of Zen temples chosen for analysis, categorised by their affiliation with the Rinzai and Sōtō schools. The chosen temples represent both historical and modern examples within each tradition, offering a comprehensive view of the architectural evolution in Zen practice.

Table 1. Selected temples for the study

Temple	Rinzai	Sōtō
Historical	Kennin-ji 建仁寺	Eihei-ji 永平寺
	Nanzen-ji 南禅寺	
Modern	Kinkaku-ji 金閣寺	Sōji-ji 總持寺

Source: own work.

RESULTS AND DISCUSSION

Architectural characteristics of Kennin-ji (建仁寺)

Kennin-ji, one of the 15 main temples of the Rinzai school and a top-ranking temple in the *gozan* system, was founded in 1202 as one of Japan's first Zen temples (Lee, 2017). Its founding abbot was Eisai, and his successor, Enni Ben'en (1202–1280), later established the Tōfuku-ji temple. In the mid-13th century, Kennin-ji (Fig. 12) was destroyed by fires three times but was rebuilt under Enni Ben'en's leadership. Today, it remains one of Kyoto's most significant temples (Wrisley, 2023).



Fig. 12. Kennin-ji temple

Source: photo by Natálie Dobrovolná 2024.

Kennin-ji's layout suggests origins in the traditional *shichidō garan* design, though its current configuration differs significantly. The complex now consists of seven main structures, including the mountain gate, Dharma hall, and washrooms. A nearby monks' hall, once part of the main complex, is now associated with a sub-temple.

The mountain gate, originally from Annei-ji temple in Shizuoka Prefecture, was relocated in 1923. Its foundation is clad with *ishigaki-zumi*, also called *kikkō ishizumi*, named for its turtle-shell-like pattern. This technique, common in castles, involves shaping stones for a tighter fit. The gate's floor is diagonally tiled, and its rounded columns rest on elaborately shaped foundation stones resembling *soban* bases. The gate has two roofs: an upper saddle-gabled roof with fan-shaped rafters and a lower roof with parallel rafters. The lower-level consoles, placed only on columns, leave space for decorative posts, while the upper-level consoles include minimal decoration. Traditional features include *katōmado* windows, *waraza* panel doors, *kibana* beam projections, and simple spiral carvings. *Shirin* is absent under both roofs (Caname Jisha Co., 2017a).

The Dharma hall shares the mountain gate's *ishigaki-zumi* cladding. Its floor is diagonally tiled with black slate stone, incorporating *soban* bases. The columns, rounded at both ends like *chimaki*, support closely spaced, single-tiered consoles forming a continuous line. The roof is a false *mokoshi* with a saddle-gabled upper section,

supported by continuous consoles. The hall exemplifies Zen architecture, with parallel rafters under the lower roof and fan-shaped rafters under the upper roof. Architectural elements include *katōmado* windows, *waraza* panel doors, and worn white paint accentuating *kibana* projections with spiral carvings. The interior has a simple wooden aesthetic with minimal white paint highlighting details. Flooring and columns with *soban* bases match the interior. Some columns are reinforced by metal fittings due to visible cracks. Notable features include shrimp-shaped beams, a mirrored ceiling, and non-continuous consoles framing it. The ceiling features a dragon painting added in 2002, first painted on paper before being affixed (Stavros, 2017; Shokoku-ji school, 2020).

The washrooms are simple and functional, with a single-storey gabled roof and exposed wooden elements highlighted by white paint. Key features include *katōmado* windows, *waraza* panel doors with integrated hinges, round *chimaki* columns on *soban* bases and visible *kibana* beam projections. The roof is upheld by beams and posts instead of continuous consoles. The foundation sits at ground level, with only a curb separating it from the surroundings.

Architectural characteristics of Nanzen-ji temple (南禅寺)

Nanzen-ji temple in Kyoto holds historical and architectural significance. Founded in 1264 by Emperor Kameyama as a retreat, it later became a Zen temple and, in 1334, attained the highest rank in the gozan system, a status it still holds. During the Muromachi period (1336–1573), only monks with prior gozan experience could serve as abbots. Despite multiple fires, including the most recent in 1895, Nanzen-ji's architectural integrity remains a subject of study, though it was never fully restored to its original or largest form (Dougill, 2017).

The temple complex has been reconstructed several times, diverging from its original Zen *shichidō garan* layout. While the mountain gate, Dharma hall, and monk's hall remain properly positioned, the Buddha hall is absent, and essential facilities such as washrooms, latrines, kitchens, and dining areas are either missing or unmarked on the temple's current map, aside from visitor restrooms (Fig. 13).



Fig. 13. The mountain gate of Nanzen-ji temple (left) and the interior of the Dharma hall (right)

Source: photos by Natálie Dobrovolná 2024.

Nanzen-ji's wooden mountain gate features two storeys but lacks white detailing. Its saddle-hip roof is supported by fan-shaped rafters in the upper section and parallel rafters in the lower. The foundation follows the *kiri-ishizumi* style with diagonal stone flooring. *Soban* bases support the columns, which have angled tops but flat lower sections reinforced with metal fittings for stability. The gate includes panel-style doors with *waraza* elements for hinges and *katōmado* windows. Both upper and lower console beams are continuous (Richie & Georges, 2012).

The Dharma hall follows the traditional Zen style, with a finely cut stone foundation distinct from typical *kiri-ishizumi* but still adhering to traditional methods. Its *chimaki*-shaped columns rest on stone *soban* bases without reinforcement. The building features panel doors, *katōmado* windows, and *waraza* projections highlighted in white. Its upper saddle-hip roof is supported by continuous consoles, while the lower *mokoshi* roof rests on beams and posts, with decorative supports filling the gaps. Both roofs lack fan-shaped rafters, as well as the *shirin* element. The interior includes a mirrored ceiling with a circular dragon depiction, framed by continuous consoles decorated with *kibana*. Shrimp-shaped beams and *chimaki* columns provide structural support. The floor consists of diagonally laid stone tiles, though this is not visible from the exterior.

Nanzen-ji's architecture exemplifies traditional Zen aesthetics and the evolution of Buddhist temple construction in Japan. Its use of natural materials and adherence to structural elements such as fan-shaped rafters, parallel rafters, and *chimaki* columns highlight its significance in the Zen architectural tradition (Tezuka, Lee, Takakura & Kambayashi, 2021).

Architectural features of Kinkaku-ji temple (金閣寺)

Kinkaku-ji, the central pavilion of Rokuon-ji temple, is renowned for its golden exterior and stands as a key example of Japanese religious architecture. Originally built in 1397 as shogun Ashikaga Yoshimitsu's retirement villa, it was converted into a Zen temple after his death in 1408. By the late 15th century, Rokuon-ji influenced the design of Ginkaku-ji temple. The complex has been destroyed multiple times, most recently in 1950 when a monk set fire to the Kinkaku-ji. Rebuilt in 1955, it remains a major tourist attraction and a UNESCO World Heritage site (Dougill, 2017).

Despite its vast grounds, Rokuon-ji retains only the kitchen from its original Zen layout. Unlike traditional Zen temples, its buildings are not arranged along two axes, and the small, single-storey entrance gate does not conform to the typical mountain gate design. The temple kitchen, though built from traditional materials, is architecturally unremarkable, featuring a single-storey structure with a gabled roof, resembling the washrooms at Kennin-ji temple.

Kinkaku-ji itself deviates from typical Zen architecture. Though incorporating some Zen elements, its gilded upper floors contrast sharply with the minimalist Zen aesthetic. The lower floor, modestly decorated, does not follow Zen architectural conventions but instead blends three distinct styles. The top floor, following Zen principles, includes Zen-style windows (*katōmado*), panel doors, and *waraza* projections. The middle floor adopts *buke-zukuri*, the samurai residential style of the Muromachi period, while the ground floor reflects *shinden-zukuri*, the aristocratic style of the Heian period. However, the structure lacks key Zen architectural features such as round columns, *soban* stone bases, diagonal flooring, stone foundations, fan-shaped rafters and *kibana* decorative elements (Cram, 2011). Thus, Kinkaku-ji's architecture exemplifies an eclectic fusion of styles, setting it apart from traditional Zen temples. While its upper floor reflects Zen influences, its overall design contrasts with the simplicity typical of Zen temple architecture, mirroring the cultural and political dynamics of its time.

Architectural features of Eihei-ji temple (永平寺)

Eihei-ji temple, founded in 1244 by Zen master Dōgen, is a key site of the Sōtō school of Zen. After studying under Myōzen at Kennin-ji temple, Dōgen became a leading figure in Japanese Zen Buddhism. Originally named Daibutsudō, it was renamed Eihei-ji in 1246, cementing its role in the Sōtō tradition. Despite damage from fires and war in 1477, Eihei-ji remains a major Zen temple. Its layout follows the Southern Sung style, introduced by Gikai from China, with seven essential structures arranged in the traditional Zen anthropomorphic pattern (Dougill, (2017).

Eihei-ji's architecture primarily features wooden gable-roofed buildings, maintaining Zen simplicity (Yokoyama, 1967). The mountain gate has two true storeys, with parallel rafters on the lower roof and fan-shaped rafters above. It lacks *kibana* carvings and white-painted wood but includes *katōmado* windows and a visible *shirin* element in its console gaps.

The Buddha hall has one true and one false *mokoshi* roof, with fan-shaped rafters on top and parallel rafters below. The structure lacks continuous consoles but features intricate console gaps. Its *chimaki* columns rest on *soban* stone bases, and *kibana* spiral motifs decorate the beams. The *ishigaki-zumi* stone foundation enhances its minimalist aesthetic. While the exterior exemplifies Zen architecture, the interior deviates, replacing the mirrored ceiling with square-patterned wood panels and intricate Buddhist figure carvings on the beams.

The Dharma hall, though built from traditional materials, diverges from Zen conventions (Yokoyama, 1967). It sits on a high *ransekizumi*-style rough stone platform, with square pillars lacking *soban* bases and a single gable roof instead of the expected *mokoshi* structure. Parallel rafters have white-painted ends, and *katōmado*-style windows are rectangular and flush with the pillars. The panel doors lack *waraza* projections, and the upper panel matches the plaster walls, further straying from Zen norms. The plain exterior lacks carvings.

Inside, the Dharma hall does not follow Zen standards. While it has tatami flooring and round columns, they lack rounded ends. The beams feature latticework and carvings, but mirrored ceilings, *kibana*, and shrimp-shaped beams are absent. Instead, gold decorations, intricate beam carvings, and patterned wallpaper around the altar mark a shift from Zen minimalism. Eihei-ji exemplifies a fusion of traditional Zen principles with decorative deviations, reflecting both its historical importance and the evolution of Zen architecture over time. Though its exterior maintains key Zen features, its interior showcases a move toward elaborate designs, illustrating the dynamic nature of Japanese Zen temple architecture.

Architectural features of Sōji-ji temple (總持寺)

Sōji-ji, founded in 1322, is crucial in the history of Zen Buddhist temples, especially within the Sōtō school. Originally on the Noto Peninsula, it was relocated to Yokohama in 1911 after a fire in 1898. The temple's reconstruction, including the mountain gate completed in 1969, integrated both traditional and modern elements, marking a departure from conventional Zen architecture. The temple's layout deviates from the traditional *shichidō garan* (seven-hall) arrangement. Although it includes all seven structures, their placement and naming differ, with the Dharma hall and Monk's hall adopting non-traditional names. Modern features, such as the use of concrete instead of wood and the spread-out kitchen and dining areas, reflect a shift toward contemporary design (Irizarry, 2022).

The Sōji-ji mountain gate, built with concrete, mimics traditional features such as two storeys with parallel and fan-shaped rafters but departs from Zen norms through large gaps filled with supports between columns and consoles, and the inclusion of *shirin*, typically absent in Zen structures. The Buddha hall, made of wood, incorporates modern elements like white-painted beam ends and stone-like cladding, lacking traditional *shirin* under the roofs and featuring densely arranged upper-storey consoles. It also includes *kibana* and spiral carvings, adapted to the temple's modern design. The Dharma hall, constructed from concrete, uses square

columns instead of traditional rounded ones. Its *kiri-ishizumi* foundation is typical of Zen, but its low height and lack of a *mokoshi* roof set it apart. The doors are dark with gold insignia, further departing from traditional wooden panel doors (Heine, 2023).

The Monk's hall follows similar innovations, with sliding doors, concrete pillars, and a lack of the *mokoshi* roof. Its sparse interior and linoleum floor contrast with the traditional Zen features, such as diagonal tile patterns. Sōji-ji exemplifies a modern reinterpretation of Zen architecture, blending contemporary design elements with traditional features. Its reconstruction represents both a departure from and an adaptation of Zen architectural norms, marking a significant evolution in the architectural history of Zen temples. Table 2 presents a comparison of Zen features in studied temples.

Table 2. Comparison of Zen features in studied temples

Element	Definition	Rinzai			Sōtō	
		historical		modern	historical	modern
		Kennin-ji	Nanzen-ji	Kinkaku-ji (Rokuon-ji Complex)	Eihei-ji	Soji-ji
shichidō garan	temple complex with seven halls	yes, but different layout	no	yes, but different layout	yes	yes, but different layout
shihanjiki	tiles diagonally on the floor	–	yes	–	–	–
chimaki	columns with rounded ends	yes	yes	–	yes	–
soban	carved stone column base	yes	yes	–	yes	–
ebi koryō	curved shrimp-shaped beam	yes	yes	–	–	–
tsumegumi	bracket complexes	yes	yes	–	–	yes
shirin	non-structural transition between the beams	–	–	–	yes	yes
	parallel rafters	yes	yes	–	yes	yes
	fan-shaped rafters	yes	yes	–	yes	yes
mokoshi	decorative roof under the real roof	yes	yes	–	yes	no
kibana	beam endings with spiral motifs	yes	yes	–	yes	yes
unryū	painting of a dragon in the clouds	yes	yes	–	–	–
katōmado	wooden windows with flower-shaped or lantern-like designs	yes	yes	yes	yes	–
sankarad/sangarado	panel doors	yes	yes	yes	yes	–
waraza	ornamental wooden projections	yes	yes	yes	–	–
	material	wood and stone	wood and stone	wood and stone	wood and stone	concrete and wood
	square columns	–	–	–	yes	yes
	mirrored ceiling	yes	yes	–	–	–

Source: own work.

DISCUSSION

The architecture of Zen temples reflects a remarkable diversity, shaped by both historical traditions and contemporary adaptations, influenced by factors such as cultural shifts, aesthetic considerations, and the integration of modern practices. Temples like Sōji-ji and Muro-ji exemplify the historical evolution of Zen temple architecture, adapting to the changing social and religious landscapes in Japan (Fowler, 2005; Irizarry, 2022). The Four Great Temples of the 7th century laid the foundation for architectural styles that influenced later designs, underscoring the importance of historical context in understanding modern structures (McCallum, 2008). Aesthetic considerations are central to Zen temple architecture, with the concept of aesthetics merging beauty with spiritual truth, which continues to inform contemporary practices (Bäumer, 2010). The layout of Zen temples, including elements like the tea house, reflects a blend of functionality and symbolic meaning, serving both practical and spiritual purposes. In contemporary designs, Zen temples are increasingly being adapted to meet the diverse needs of modern communities, as seen in Sōji-ji's engagement with its local population (Irizarry, 2022). Despite these changes, some argue that the evolution of Zen temple architecture may dilute traditional practices, potentially leading to a loss of historical authenticity in favour of modern relevance.

Despite identifying several architectural features in the analysed temples, none of the buildings contained all of these elements simultaneously. Instead, the features appeared in varying combinations, accompanied by deviations from the traditional traits – some subtle and others more noticeable. While most of the analysed temples adhere to the most prominent architectural characteristics, Sōji-ji, one of the two central temples of the Sōtō school, notably deviates from the typical layout of *shichidō garan* and is constructed primarily from concrete rather than wood. This deviation challenges the typical architectural principles described by Yokoyama (1967) but also addresses the question of how modern Zen temples differ architecturally from historical ones. The arrangement of buildings within the Sōji-ji complex further demonstrates that the Sōtō school does not strictly adhere to the *shichidō garan* layout.

In contrast, the temples of the Rinzai school supported the hypothesis that the composition of their temple complexes historically followed the principles of *shichidō garan*. However, over time, the layout of these complexes has evolved to such an extent that none of the Rinzai temples studied can be precisely categorised as *shichidō garan*. This observation suggests that while Yokoyama (1967) outlines the *shichidō garan* layout as a key architectural characteristic of Zen temples, it does not apply to the Rinzai school. Additionally, the presence of a monk's hall in some of the Rinzai temples contradicts Collcutt's (1981) assertion that such halls had completely disappeared or were replaced by the Zen hall. Notably, no Zen hall was identified in any of the analysed Rinzai temples.

The diversity in Zen temple architecture complicates the assessment of how much it has evolved since Yokoyama's time (1967). His outlined features predominantly correspond to the architecture of historical temples, but more modern temples, such as Rokuon-ji, deviate significantly from these norms. It can be assumed that Zen architecture continues to evolve and is likely to move further away from these traditional features.

Furthermore, this study sought to determine whether the identified architectural features could reliably indicate whether a building was constructed in the Zen architectural style. When focusing on a single architectural element, the result may be inconclusive. However, the more elements that are considered in the analysis, the more reliably the building can be categorised as Zen. The Kinkaku-ji building at Rokuon-ji exemplifies that the presence of several Zen-style features does not necessarily mean that the building follows the purely Zen architectural style. In fact, Kinkaku-ji is constructed in an eclectic style.

The research suggests that the *shirin* element, which is typically used in other architectural styles to fill empty spaces under the roof, is not a typical feature of Zen architecture due to its minimal occurrence. This finding corroborates Yokoyama's assertion from 1967, though exceptions exist in which *shirin* can be

identified in Zen temple buildings. However, no instances were found in which the *shirin* appeared as complex as it is described in the JAANUS online dictionary. In general, the presence or absence of certain elements in the studied temples proved to be typical of Zen architecture, though not universal.

Integrating Zen architectural principles into contemporary building practices is a promising way to enhance architectural sustainability (Sinclair, 2016; Mazzola, 2022). This potential stems from the thoughtful use of natural materials, passive environmental controls, community-rooted design, and evolving technologies, which together reflect a holistic approach to sustainable development. By using natural materials such as wood and traditional designs, contemporary architecture can achieve a balance between environmental responsibility and cultural heritage. This synthesis of old and new approaches can lead to innovative solutions that address today's sustainability challenges. Zen temples often use wood, which not only provides aesthetic value, but also enhances sustainability due to its renewability and low carbon footprint (Zou & Bahauddin, 2024). In addition, the cultural significance of these materials fosters a connection between the community and their heritage, promoting a sense of place and identity (Zou & Bahauddin, 2024). Traditional temples, particularly in warm, humid climates, incorporate passive design features that optimise thermal performance and reduce reliance on mechanical cooling systems, which can be adapted to modern buildings to improve energy efficiency and occupant comfort while respecting local climatic conditions (Sarkar & Panicker, 2024).

Furthermore, adopting digital tools like building information modelling (BIM) enables the precise integration of traditional architectural elements into new designs. This enhances sustainability compliance without compromising cultural integrity (Bazerbashi, Olabi & Aslan, 2024). This approach not only preserves cultural identity but also improves the environmental performance of new buildings (Bazerbashi et al., 2024). Although BIM plugins for timber construction already exist, integration between timber construction governmental planning and BIM software is still needed. Finland's Construction 2000 classification system is an example of supporting the development of BIM in design, cost estimation, and production planning in timber construction (Calquin et al., 2024). Importantly, digital technologies enable detailed simulations of material efficiency, thermal performance, and life-cycle assessment. Prior digital-simulation-based studies have indicated that traditional Japanese residential architecture can significantly reduce energy use while improving indoor environmental quality (Pourbakht, 2025). Buragohain, Buragohain, Meng, Deng and Chaudhary (2025) evaluated scanning and three-dimensional modelling of temples as successful tools for heritage preservation. In addition, virtual reality with a digital representation of temples in Japan became a form of promotion. While it attracted a young audience, it may also contribute to the loss of the essence of traditional Zen teachings (Buragohain et al., 2025). Three-dimensional scanning may also be useful for analysis of the building elements and possibilities of further reuse of materials (Keulemans, Harle, Hashimoto & Mugavin, 2020). Innovation in technology is, therefore, essential to contemporary green building strategies and heritage preservation. Table 3 provides a concise overview of how Zen architectural principles relate to sustainability. It summarises key architectural features in relation to the environmental, societal, and economic dimensions of sustainable development.

This summary also emphasises the multifaceted nature of sustainability in Zen architecture and its potential to promote cultural preservation and ecological responsibility. Nevertheless, several challenges remain. One of them is ensuring disaster resilience as climate change brings more frequent and unpredictable weather events. Additionally, as wood plays a central role in the sustainable design of traditional Zen temples, sustainable forestry is a significant challenge that must be considered. The dangers of production-focused policies highlight the importance of flexible, locally tailored approaches to forest management (Yamada, Kanomata, Shimizu, Murakami & Yamaura, 2025). Moreover, advanced digital modelling and simulation studies are necessary to better quantify the impact of passive design elements on actual energy performance in Zen temples. Lastly, preserving the essence of Zen tradition is crucial, as its profound spatial symbolism is often lost on tourists unfamiliar with its deeper meaning.

Table 3. Sustainability in Zen temple architecture

Category	Features that support sustainable development		Challenges
Society	Preserving the architectural and cultural heritage		Need for innovation and natural disaster-resilient design
	Local craftsmanship		
	Local identity		
	A well-integrated indoor-outdoor flow with a mindfully designed garden promotes wellness and tranquillity		
Environment	Renewable and reusable materials (wood)		Rising wood demand requires changes in forestry policies
	Materials with low-embodied energy (wood, stone)		
	Non-toxic materials (wood, stone, paper, straw)		
Economy	Passive design strategies	Thermal mass (stone)	Need for further research to better understand the actual impact of passive design strategies on energy efficiency
		Elevated floor and open floorplan for improved ventilation	
		Focus on natural lighting	
		Broad eaves protect from solar radiation in summer and allow solar energy gain in winter, when the sun is lower	
	Recycling – using buildings from another location		
	Improvement of the attractiveness of the city and promoting tourism		Risk of loss of the essence by the commercialisation of the tradition

Source: own work.

Given that this study focused on a narrow range of temples, the results should not be viewed as definitive rules for all Zen architecture. Future research could expand the scope by including additional architectural elements or temple complexes, or it could focus on a more detailed study of a smaller subset, such as the central temples of the *gozan* system located in the cities of Kamakura and Kyoto. Other avenues for expanding the research could involve comparisons of potential differences between temples located in northern and southern Japan, influenced by the region's varying climates, or examining differences in the architecture of rural versus urban temples.

CONCLUSION

This study provides a comprehensive analysis of Zen temple architecture, revealing a significant evolution in the design of these temples. The architecture of the selected Zen temples demonstrates considerable variability in its adherence to traditional features, with no single building fully conforming to the historical architectural norms of Zen. While some temples retain key elements, others, particularly in the Rinzai school, have evolved further from the traditional *shichidō garan* layout, suggesting a growing divergence from historical conventions.

The study also highlights the incorporation of modern materials, such as concrete, and more flexible layouts in contemporary Zen temples. This shift marks a departure from the traditional use of wood and standardised design, reflecting broader changes in construction methods and materials. However, these innovations also offer opportunities to integrate sustainable practices into Zen architecture, combining traditional elements with modern environmental needs.

The findings demonstrate that Zen temple architecture can inform sustainable design methodologies, particularly through the use of natural materials, passive design principles, and cultural integration. These findings make Zen temple architecture a valuable reference for contemporary architectural practice, especially in the context of ecological design and wooden structures. Furthermore, the study emphasises the importance of incorporating these insights into architectural education. Integrating Zen architectural principles into teaching curricula can foster a deeper understanding of sustainable building strategies and enhance proficiency in designing with renewable, low-impact materials.

The findings underscore that Zen temple architecture, while maintaining its cultural and spiritual heritage, is evolving to meet contemporary needs. The integration of modern design and materials into traditional forms offers a path toward more sustainable and environmentally conscious architecture. More cross-cultural research is needed to compare how Zen architectural principles are interpreted and adapted in different regions and internationally. Future research could further explore how these principles can be adapted to balance sustainability with the preservation of cultural values, ensuring that Zen temples continue to evolve in harmony with both tradition and the pressing environmental challenges of our time.

Authors' contributions

Conceptualisation: N.D., M.S. and M.D.V.; methodology: N.D.; formal analysis: N.D., M.S. and M.D.V.; investigation: N.D.; data curation: N.D. and M.S.; writing – original draft preparation: N.D., M.S. and M.D.V.; writing – review and editing: M.D.V.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Bazerbashi, S., Olabi, S. & Aslan, H. (2024). Adapting Traditional Sustainable Architectural Elements in Modern Buildings Utilizing Modern BIM Technologies. *International Journal of BIM and Engineering Science (IJBES)*, *9* (1) 45–66. https://doi.org/10.54216/IJBES.090106

Bäumer, B. (2019). The Living Temple: Aesthetics n Śilpa Śāstra. In K.D. Tripathi, P. Ghosal (Eds), *Meaning and Beauty, Shastric Foundation of Indian Aesthetics* (pp. 181–215). New Delhi: IGNCA & Aryan Books International.

Bodiford, W. M. (2025, June 19). Zen. In *Encyclopedia Britannica*. https://www.britannica.com/topic/Zen [accessed: 28.06.2025].

Borup, J. (2008). *Japanese Rinzai Zen Buddhism: Myōshinji, a Living Religion* (Numen Book Series, 119). Brill.

Buragohain, D., Buragohain, D., Meng, Y., Deng, C. & Chaudhary, S. (2025). A metaverse based digital preservation of temple architecture and heritage. *Scientific Reports*, *15*, 15484. https://doi.org/10.1038/s41598-025-00039-w

Calquin, D. L., Mata, R., Correa, C., Nuñez, E., Bustamante, G., Caicedo, N., Fernandez, D. B., Díaz, M., Pulgar-Rubilar, P. & Roa, L. (2024). Implementation of Building Information Modeling Technologies in Wood Construction: A Review of the State of the Art from a Multidisciplinary Approach. *Buildings*, *14* (3), 584. https://doi.org/10.3390/buildings14030584

Caname Jisha Co. (2017a). 建仁寺　（けんにんじ [Kennin-ji]. Retrieved from https://www.caname-jisha.jp/cms/?p=916 [accessed: 28.06.2025].

Caname Jisha Co. (2017b). 基壇（きだん）とは [*What is Kidan?*] Retrieved from https://www.caname-jisha.jp/cms/?p=1117 [accessed: 28.06.2025].

Collcutt, M. (1981) *Five Mountains: The Rinzai Zen Monastic Institution in Medieval Japan*. Cambridge: Harvard University Press.

Cram, R. A. (2011). *Impressions of Japanese architecture and the allied arts*. North Clarendon: Tuttle Publishing.

Discoe, P. & Quinn, A. (2008). *Zen Architecture: The Building Process as Practice*. Layton: Gibbs Smith.

Dougill, J. (2017). *Zen Gardens and Temples of Kyoto: A Guide to Kyoto's Most Important Sites*. North Clarendon: Tuttle Publishing.

Dumoulin, H. (2005). *Zen Buddhism: Japan* (Vol. 2). Bloomington: World Wisdom.

Faulkes, B. D. A. (1994). *Politicized aesthetics: reclusion literature in the Late Heian and Early Kamakura eras of pre-modern Japan* (doctoral dissertation). University of British Columbia. http://hdl.handle.net/2429/5194

Fowler, S. D. (2005). *Muroji: Rearranging Art and History at a Japanese Buddhist Temple*. Honolulu: University of Hawaii Press. https://doi.org/10.1515/9780824874582

Goble, A. E. (2007). Medieval Japan. In W. A. Tsutsui (Ed.), *A Companion to Japanese History* (pp. 47–66). Wiley-Blackwell. https://doi.org/10.1002/9780470751398.ch4

Heine, S. (2011). *Sacred High City, Sacred Low City: A Tale of Religious Sites in Two Tokyo Neighborhoods*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780195386202.001.0001

Heine, S. (2015). *Dogen and Soto Zen*. Oxford: Oxford University Press.

Heine, S. (2017). *From Chinese Chan to Japanese Zen: a remarkable century of transmission and transformation*. Oxford University Press. https://doi.org/10.1093/oso/9780190637491.001.0001

Heine, S. (2021). *Dogen: Japan's original Zen teacher* (Vol. 8). Shambhala Publications.

Heine, S. (2023). "For the First Time in Japan": The Main Elements of Hangzhou-Based Zen That Dōgen Transmitted. *Religions*, *14* (8), 1021. https://doi.org/10.3390/rel14081021

Irizarry, J. A. (2022). *Sojiji: Discipline, Compassion, and Enlightenment at a Japanese Zen Temple* (Michigan Monograph Series in Japanese Studies, 94). Ann Arbor: University of Michigan Press.

Japanese Architecture and Art Net Users System [JAANUS] (2001). *Shirin* 枝輪. Retrieved from https://www.aisf.or.jp/~jaanus/ [accessed: 28.06.2025].

Kage, T. (2022). Japanese Daimyōs as Sea Lords in the 15th and 16th Centuries: Their Involvement in the Japan–Ming Trade. In M. Oka (Ed.), *War and Trade in Maritime East Asia. Palgrave Studies in Comparative Global History* (pp. 31–57). Singapore: Palgrave Macmillan. https://doi.org/10.1007/978-981-16-7369-6_3

Kase, K., Choi, E. & Nonaka, I. (2022). Ideology and Rules. In *Dr Kazuo Inamori's Management Praxis and Philosophy: A Response to the Profit-Maximisation Paradigm* (pp. 197–284). Singapore: Palgrave Macmillan. https://doi.org/10.1007/978-981-19-3398-1_4

Keulemans, G., Harle, J., Hashimoto, K. & Mugavin, L. (2020). Design considerations for the transformative reuse of a Japanese temple. *Proceedings of DRS*, *1*. https://doi.org/10.21606/drs.2020.183

Ku, Y. H. (2016). *History of Zen*. Singapore: Springer. https://doi.org/10.1007/978-981-10-1130-6

Lee, J. H. X. (Ed.) (2017). *Japanese Americans: The History and Culture of a People*. London: Bloomsbury Academic.

Lin, L. (2017). Roof Structure of Japanese Zen-Style Buddha Halls. In *International Conference on East Asian Architectural Culture* (pp. 502–513). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-75937-7_38

Lomas, T., Etcoff, N., Van Gordon, W. & Shonin, E. (2017). Zen and the art of living mindfully: The health-enhancing potential of Zen aesthetics. *Journal of Religion and Health*, *56*, 1720–1739. https://doi.org/10.1007/s10943-017-0446-5

McCallum, D. F. (2008). *The four great temples: Buddhist archaeology, architecture, and icons of seventh-century Japan*. Honolulu: University of Hawaii Press.

Masaki, A. (2022). Spirituality of Japanese Buddhism considered from enlightenment of nonsentient beings. *International Journal of Educational Research*, *115*, 102019. https://doi.org/10.1016/j.ijer.2022.102019

Mazzola, E. M. (2022). Implementing the lesson of early 20th century traditional buildings for a real sustainability. The examples of Corviale (Rome) and ZEN (Palermo) districts. In *Proceedings HERITAGE 2022 – International Conference on Vernacular Heritage: Culture, People and Sustainability* (pp. 879–887). València: Universitat Politècnica de València. https://doi.org/10.4995/HERITAGE2022.2022.15633

Nagatomo, S. (2006). Japanese Zen Buddhist Philosophy. In E. N. Zalta & U. Nodelman (Eds), *The Stanford Encyclopedia of Philosophy* (Fall 2024 Edition). Retrieved from https://plato.stanford.edu/archives/fall2024/entries/japanese-zen [accessed: 28.06.2025].

Pourbakht, M. (2025). Passive Design Strategies in Traditional Japanese Architecture: A Case Studies of the Chochikukyo House. *Open Science Journal*, *10*. https://doi.org/10.23954/osj.v10i1.3685

Richie, D. & Georges, A. (2012). *Temples of Kyoto*. North Clarendon: Tuttle Publishing.

Sadler, A. L. (2011). *Japanese architecture: a short history*. North Clarendon: Tuttle Publishing.

Sarkar, A. & Panicker, J. (2024). *Passive Designs and Thermal Performance of the Temples in the Warm-Humid Climatic Zone of South India*. https://doi.org/10.29121/shodhkosh.v5.i1.2024.2374

Shokoku-ji school (2020). 境内案内 | 臨済宗相国寺派 [*Temple grounds guide*]. Retrieved from https://www.shokoku-ji.jp/kinkakuji/guide [accessed: May 2024].

Sinclair, D. B. (2016). Japanese spirituality, flexibility and design: influences and impacts on agile architecture+ open building. In *International Research Conference: Architectural Research Centers (ARCC)/European Association of Architectural Educators (EAAE), University of Lisbon, Portugal*. Portugal: European Association of Architectural Educators (EAAE).

Stavros, M. (2017). Monuments and mandalas in medieval Kyoto: Reading Buddhist kingship in the urban plan of Ashikaga Yoshimitsu. *Harvard Journal of Asiatic Studies*, *77* (2), 321–361. https://doi.org/10.1353/jas.2017.0029

Sun, F. (2025). Zen emptiness: application and exploration of Zen philosophy in modern minimalist art design. *Trans/Form/Ação*, *48* (3), e025018.

Tezuka, T., Lee, R., Takakura, H. & Kambayashi, Y. (2001). Models for conceptual geographical prepositions based on web resources. *Journal of Geographic Information and Decision Analysis*, *5* (2), 83–94.

Welter, A. (2006). Zen Buddhism as the Ideology of the Japanese State: Eisai and the *Kōzen gokokuron*. In W. Albert, D. S. Wright (Eds), *Zen Classics: Formative Texts in the History of Zen Buddhism* (pp. 65–112). https://doi.org/10.1093/0195175255.003.0004

Winfield, P. D. (2015). Embodying Sōtō Zen. In S. Heine (Ed.), *Dōgen and Sōto Zen*. New York: Oxford University Press.

Winfield, P. D. & Heine, S. (Eds) (2017). *Zen and material culture*. Oxford University Press. https://doi.org/10.1093/acprof:oso/9780190469290.001.0001

Wrisley, G. (2023). Revitalizing the Familiar. In R. H. Scott & J. McRea (Eds), *Introduction to Buddhist East Asia*. State University of New York Press. https://doi.org/10.1515/9781438492438-008

Yamada, Y., Kanomata, H., Shimizu, K., Murakami, W. & Yamaura, Y. (2025). Assessing the Sustainability of Timber Production Under Policy-Driven Logging: A Spatial Analysis from Southwestern Japan. *Forests*, *16* (6), 989. https://doi.org/10.3390/f16060989

Yokoyama, H. (1967). 横山秀哉. 禅の建築 [*Zen Architecture*]. Tokyo: Shokokusha.

Young, D. & Young, M. (2019). *Art of Japanese Architecture: History/Culture/Design*. North Clarendon: Tuttle Publishing.

Xie, Y. (2024). From Pagoda to Pavilion: The Transition of Spatial Logic and Visual Experience of Multi-Story Buddhist Buildings in Medieval China. *Religions*, *15* (3), 371. https://doi.org/10.3390/rel15030371

Zou, M. & Bahauddin, A. (2024). The Creation of "Sacred Place" through the "Sense of Place" of the Daci'en Wooden Buddhist Temple, Xi'an, China. *Buildings*, *14* (2), 481. https://doi.org/10.3390/buildings14020481

ARCHITEKTURA ŚWIĄTYŃ ZEN A ROZWÓJ ZRÓWNOWAŻONY: ANALIZA TRADYCYJNYCH PROJEKTÓW I WSPÓŁCZESNYCH ADAPTACJI W JAPONII

STRESZCZENIE

Powstały w Chinach buddyzm zen wywarł silny wpływ na architekturę japońską. Do dziś najbardziej autorytatywną publikacją dotyczącą elementów japońskiej architektury zen pozostaje książka *Zen no Kenchiku* (pl. *Architektura zen*) Hideo Yokoyamy. Współczesne świątynie zen przeszły jednak liczne przebudowy i modyfikacje, co rodzi pytanie, w jakim stopniu ich obecny wygląd pozostaje wierny projektom pierwotnym. Celem niniejszego badania jest porównanie współczesnej architektury wybranych świątyń zen z cechami architektonicznymi uznanymi za fundamentalne dla stylu architektury zen w latach 60. XX wieku. Świątynie wybrano ze względu na ich znaczenie historyczne i współczesne, ze szczególnym uwzględnieniem szkół Rinzai i Sōtō. Opisane w książce *Zen no Kenchiku* elementy zostały zweryfikowane i uzupełnione informacjami z innych źródeł i literatury przedmiotu. W wyniku analizy wykazano, że żadna z badanych świątyń nie zawierała jednocześnie wszystkich elementów zen wymienionych przez Yokoyamę. Jak pokazano, architektura zen ewoluuje i może wspierać budownictwo zrównoważone. Wyniki badania stanowią podstawę do dalszych analiz świątyń zen, szczególnie w kontekście praktyk architektury zrównoważonej.

Słowa kluczowe: architektura japońska, materiał naturalny, rozwój zrównoważony, buddyzm zen

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REVIEW PAPER

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ASSESSMENT OF THE IMPACT OF COMPREHENSIVE THERMAL MODERNISATION ON THE ENERGY EFFICIENCY OF A HISTORIC BUILDING: A CASE STUDY OF A HOUSE IN LOWER SILESIA, POLAND

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ABSTRACT

The objective of this study was to evaluate the effects of comprehensive thermal modernisation on the energy efficiency of a 19th-century residential heritage building. The central hypothesis posited that a substantial reduction in primary energy demand could be achieved without compromising the building's architectural and historical integrity. The research was conducted as a case study of an existing historic structure located in the Dolnośląskie Voivodeship of Poland. The proposed modernisation strategy involved the implementation of a ground source heat pump, mechanical ventilation with heat recovery, low-temperature underfloor heating, photovoltaic panels, and the use of natural, vapour-permeable insulation materials. A comparative analysis of the building's energy performance certificates demonstrated a significant reduction in primary energy demand (from 878.9 $kWh \cdot m^{-2} \cdot year^{-1}$ to 54.6 $kWh \cdot m^{-2} \cdot year^{-1}$), thereby confirming the research hypothesis. These findings underscore the feasibility of reconciling contemporary energy efficiency requirements with the conservation of historic architecture, provided that context-sensitive, technologically appropriate solutions are employed.

Keywords: thermal modernisation, building energy performance, building renovation, historic building

INTRODUCTION

In the context of accelerating climate change and the global pursuit of sustainable development, the construction industry has come under increasing scrutiny for its significant contributions to greenhouse gas emissions, energy consumption, and resource depletion. As buildings account for a substantial portion of global energy use and material demand, the environmental implications of decisions made during their design, construction, renovation, and demolition are critical to the broader goal of environmental stewardship. Consequently, the need to adopt more sustainable construction practices has brought renewed attention to the adaptive reuse and renovation of existing buildings as a viable alternative to new construction.

A growing body of research underscores the environmental advantages of building renovation (Ferreira, Almeida & Rodrigues, 2017; Huo, Ma, Cai, Liu & Mu, 2021; Benke, Lewis, Carlisle, Huang & Simonen, 2022; Alarcón, 2023; Rybak-Niedziółka et al., 2023; Gavu & Peiser, 2024; Starzyk et al., 2024).

According to Hasik et al. (2019), refurbishing existing structures can reduce environmental impacts by 53% to 75% across multiple categories, including global warming potential, energy use, and material

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consumption. These reductions are primarily driven by the lower demand for new construction materials and the conservation of embodied energy already present in existing structures. Similar findings have emerged from studies conducted globally (Mastrucci, Marvuglia, Benetto & Leopold, 2020; Liao, Ren, Liu, 2023; Passoni, Caruso, Felicioni & Negro, 2024; Weerasinghe, Darko, Chan, Blay & Edwards, 2024; Darko, Weerasinghe, Chan & Wu, 2025; Gillett, Kalogirou, Morthorst, Norton & Ornetzeder, 2025). For instance, a Danish life cycle assessment demonstrated that renovations employing traditional materials and methods could achieve more favourable environmental outcomes than those using contemporary construction technologies (Serrano, Kampmann & Ryberg, 2022). A Canadian study further confirmed that extending the lifespan of buildings through renovation contributes to significant reductions in life-cycle energy use (Lucuik, Huffman, Trusty & Prefasi, 2010). Complementary research from China and Austria highlights the notable decrease in carbon emissions associated with renovation compared to demolition and new construction (Gao & Li, 2008).

Beyond environmental benefits, economic considerations also support the case for renovation. Although new buildings may sometimes offer more predictable energy performance over time, major retrofits often require lower initial capital investment and shorter construction timelines. In many cases, they prove to be more cost-effective, especially in urban contexts where land availability is limited and demolition may be impractical or restricted. Fleur, Rohdin and Moshfegh (2019) point out that while renovations may not always be optimal from a life-cycle cost perspective, they can still yield favourable returns when broader economic and social factors are taken into account. Additionally, renovations often enhance a building's functionality, safety, and user comfort, while also increasing its real estate value (Martinaitis, Rogoža & Bikmaniene, 2004).

RESEARCH GOAL AND HYPOTHESIS

The primary objective of this study is to assess the effectiveness of comprehensive thermal modernisation measures in enhancing the energy performance of a 19th-century single-family heritage building, without compromising its historical and architectural integrity. Drawing on existing literature and best practices in the field of sustainable heritage conservation, the following research hypothesis was formulated: *It is possible to achieve a substantial reduction in primary energy demand while preserving the architectural and historical value of the building.*

MATERIAL AND METHODS

The investigation is structured as a case study of an existing historic building located in the village of Stary Wielisław, Dolnośląskie Voivodeship, Poland. The building, listed in the municipal register of monuments, represents a typical example of rural domestic architecture from the 19th century and is characterised by traditional construction techniques, including half-timbered walls and natural building materials.

A comprehensive architectural and construction inventory was conducted as the initial step. Drawings were prepared in Autodesk AutoCAD, and a 3D model was created in SketchUp. Based on this documentation, a series of proposed modernisation interventions were developed, aiming to improve thermal performance without compromising the building's heritage character.

Energy modelling was performed to assess the energy performance of the building, and an advanced digital model was created using ArCADia-THERMOCAD software by ArCADiasoft. This building performance simulation tool enabled a thorough analysis of the thermal characteristics of the structure, taking into account:

– the physical and thermal properties of construction materials,

– the geometry and spatial configuration of the building,
– the presence and impact of thermal bridges.

Through this modelling approach, it was possible to calculate the building's energy demand both before and after the proposed retrofitting interventions. The resulting data formed the basis for a comparative analysis of energy performance certificates (EPCs) corresponding to the pre- and post-renovation states.

The overarching objective of the methodological approach was to reconcile contemporary energy efficiency standards with the conservation of historical architectural values. This was achieved through the careful selection of renovation technologies and strategies that minimise visual and structural interference with original materials and construction details.

CASE STUDY – SINGLE-FAMILY HERITAGE BUILDING IN DOLNOŚLĄSKIE VOIVODESHIP, POLAND

Historical background

The building is located in the village of Stary Wielisław, in the Kłodzko municipality, Dolnośląskie Voivodeship, Poland. It was constructed in the mid-19th century. The earliest known depiction of the building appears on a German postcard dated 1902. Initially, the building housed a post office (Fig. 1) and was later converted into a bakery (Fig. 2) following reconstruction. After 1945, the property was vacated by its German owners, who were forced to leave due to post-war border changes. Their place was taken by settlers from the eastern borderlands of the former Polish territories, resettled as part of civilian repatriation efforts after World War II. The building is listed in the local register of historical monuments.



Fig. 1. German postcard with a picture of the house in the left corner described as a post office

Source: polska-org.pl.



Fig. 2. German postcard with a picture of the house described as a bakery

Source: polska-org.pl.

The architecture of Lower Silesia, especially Kłodzko Land, is characterised by a harmonious blend of Central European rural styles, shaped by centuries of Polish, Czech, and German influences. Typical for the region are solid stone or brick ground floors combined with timber-framed upper levels and steep, often corrugated roofs adapted to the mountain climate. The house exemplifies this vernacular tradition: its whitewashed ground floor, dark wooden upper story, and steep gabled roof reflect both practical needs and local building customs. Elements such as small dormer windows and simple, functional design emphasise the region's historical focus on durability and adaptation to its environment.

Building characteristics

The structure is a single-family residential building with an adjoining utility section. It comprises two usable storeys, an attic, and a partially underground basement located in the northwestern part. The foundation is primarily made of sandstone set in lime mortar. The ground-floor walls are built of brick, with the exception of the southwestern corner, which is constructed from timber logs. The upper storey is built using a half-timbered (or Prussian wall) technique, consisting of a wooden frame filled with a clay-and-chaff mixture. The attic spans the full area above the upper floor. The roof is a mansard type with gablets and three dormer windows on the northern side. It is currently covered with asbestos-cement sheets, though the original roofing material was wooden shingles. The ceilings are timber-framed and plastered from below with clay-based plaster applied on reed matting. The exterior façade is white, featuring lime plaster mixed with slag aggregate in a roughcast finish known locally as *baranek*. The main entrance consists of a double-leaf wooden door framed by a sandstone portal. The windows are traditional wooden box-type (Figs 3–7).



Fig. 3. Current state, north-east corner

Source: Authors' own photo.



Fig. 4. Current state, south-east corner

Source: Authors' own photo.

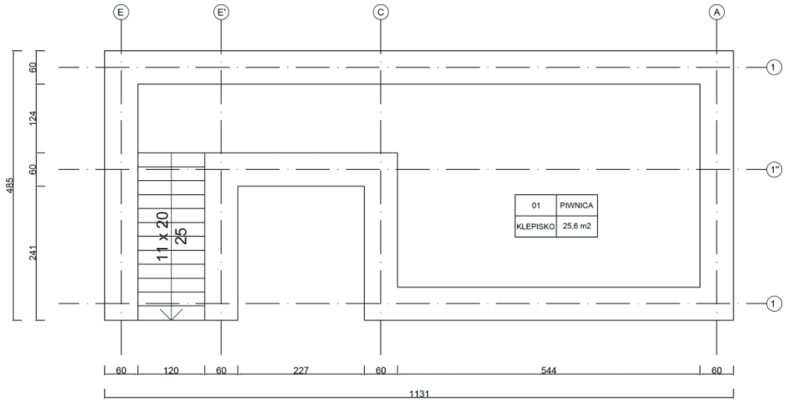


Fig. 5. Underground floor plan

Source: Authors' own photo.

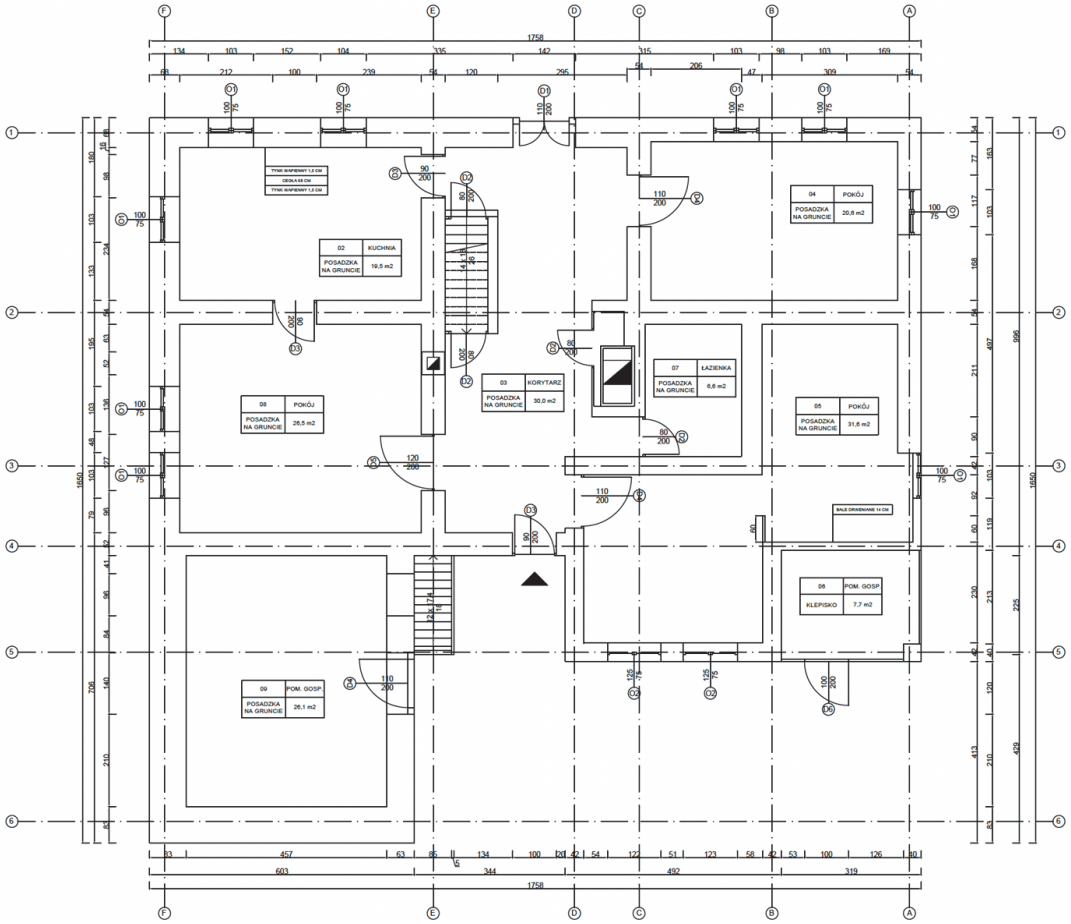


Fig. 6. First floor plan

Source: own work.

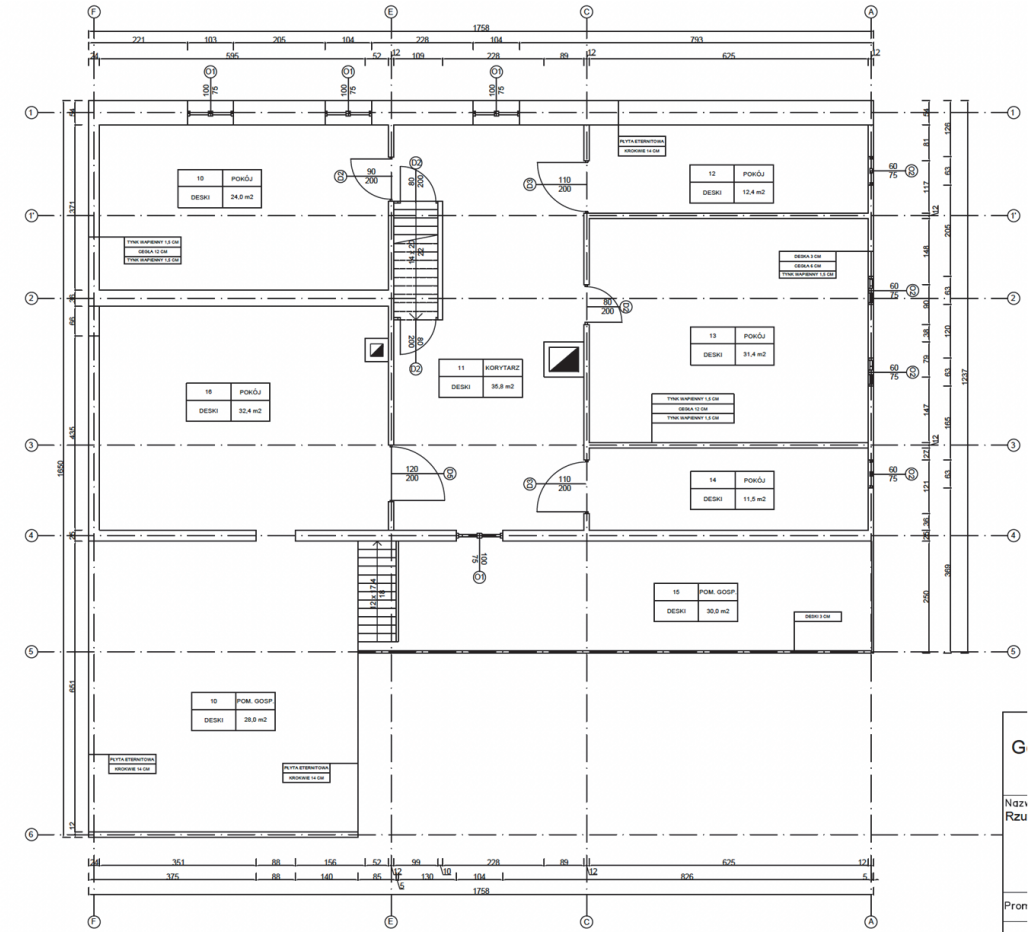


Fig. 7. Second floor plan

Source: own work.

Identified problems

1. Moisture penetration in ground-floor walls

The masonry walls on the ground floor exhibit significant moisture-related degradation. The lime mortar used in the foundation walls acts as a capillary medium, drawing groundwater upwards in the absence of any horizontal or vertical damp-proof barriers. This uncontrolled moisture rise leads to saturation at the base of the walls and the gradual upward migration of water. Additionally, the application of cement-lime plaster in certain interior spaces exacerbates the problem due to its low vapour permeability. As a result, vertical capillary channels are formed, impeding the natural evaporation of moisture. In contrast, bare masonry or walls coated with high-permeability plasters facilitate faster and lower-level moisture dissipation. For an extended period, the building lacked an appropriate rainwater drainage system, causing direct exposure of the masonry to runoff from the roof. Despite prior attempts to mitigate the damage using biocidal treatments, the persistent high moisture content has led to the proliferation of microorganisms such as moulds, bacteria, algae, and yeast. These organisms actively contribute to the biological corrosion of the wall structure. Moreover, their presence

poses a health risk to occupants, potentially causing allergic reactions, fungal infections, and respiratory diseases. Mycotoxins released by moulds are known to be toxic to both humans and animals.

2. Biological corrosion and degradation of timber components

The building features wooden structural elements in several key areas. The floors are constructed from timber joists supported directly on masonry walls. The first-floor walls utilise a traditional half-timbered (fachwerk) system, consisting of a wooden frame filled with a mixture of clay and chopped straw. The roof is supported by a rafter-collar beam system, without boarding, with asbestos-cement sheets mounted directly onto the purlins. The southwest corner of the ground floor is built from horizontally laid timber logs. In all these areas, the wooden components have suffered from advanced biological decay and material fatigue, primarily due to long-term neglect and inadequate maintenance. Signs of rot, insect infestation, and structural weakening are evident, threatening the building's integrity and necessitating conservation-oriented interventions.

3. Asbestos-cement roofing

The roof is covered with asbestos-cement sheets, a material widely used in Poland and former Eastern Bloc countries during the 20th century. Despite its durability, affordability, and ease of manufacture, asbestos in particulate form is highly carcinogenic. Inhalation of asbestos fibres is associated with severe health conditions, including asbestosis, lung cancer, and malignant pleural mesothelioma (O'Reilly, Mclaughlin, Beckett & Sime, 2007). In addition, the roofing material has deteriorated significantly and exhibits numerous leaks, some of which have been temporarily patched using metal sheets. According to current Polish legislation, all asbestos-cement roofing must be removed and safely disposed of by 2032.

4. South-facing extension

At some point – most likely during the building's conversion from a post office to a bakery – a series of extensions were added to the south side. These consist of a masonry ground-floor addition and timber extensions on both the ground and first floors. This annexe disrupts the original geometry of the building and significantly reduces natural light in the interior spaces due to shading effects.

Proposed architectural interventions

In response to the identified issues, a conceptual architectural design has been developed with the aim of restoring the original form of the building while enhancing its functional performance. The proposed interventions include:

- Reconstruction of the original roof shape (Figs 8–9) and replacement of asbestos-cement sheets with historically appropriate roofing materials (e.g. wooden shingles or slate).
- Preservation of historically significant features, such as wooden windows and doors, using current technology to create wooden box windows with a heat transfer coefficient of $U = 1.1$ W·m^{-2}·K^{-1}, as well as the distinctive timber-framed corner of the building.
- Removal of the south-facing extension, restoring the building's original massing and improving interior daylight access.
- Reconfiguration of the first-floor layout (Fig. 10) to better meet contemporary residential needs.
- Insertion of additional windows (Figs 10–11) to enhance natural lighting and ventilation.
- Creation of a dedicated technical space for the integration of thermal modernisation systems, including mechanical ventilation, insulation upgrades, and renewable energy solutions.

The proposed interventions aim to strike a balance between the preservation of cultural heritage and compliance with modern energy efficiency and comfort standards.

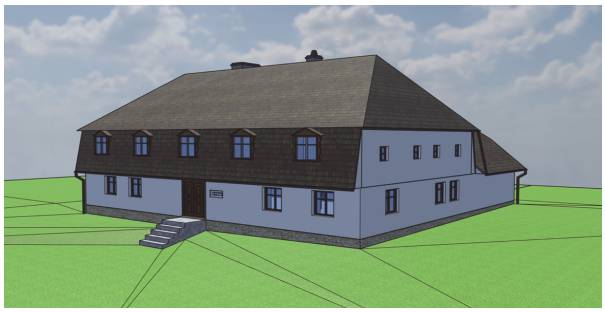


Fig. 8. 3D model of the building created in SketchUp, north-west corner

Source: own work.



Fig. 9. 3D model of the building created in SketchUp, south-east corner

Source: own work.

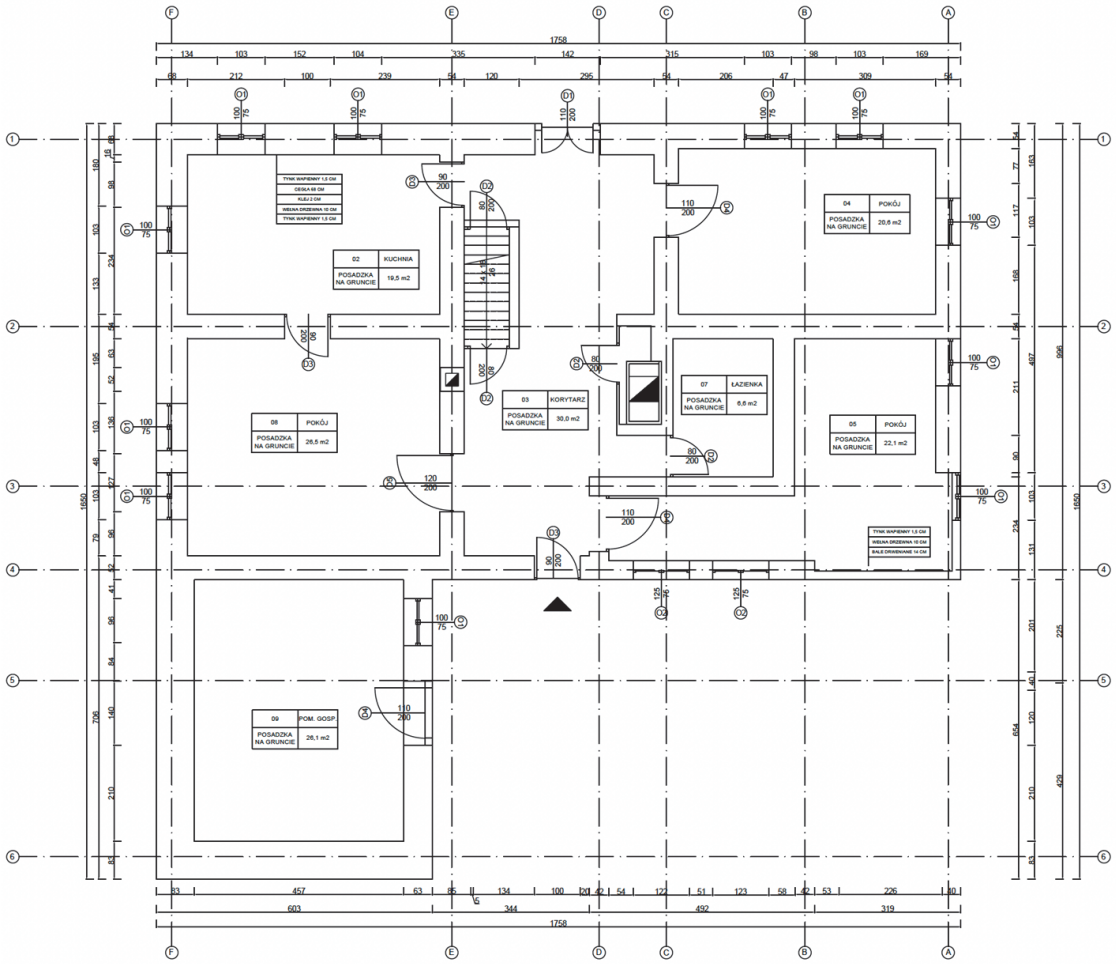


Fig. 10. First floor after renovation

Source: own work.

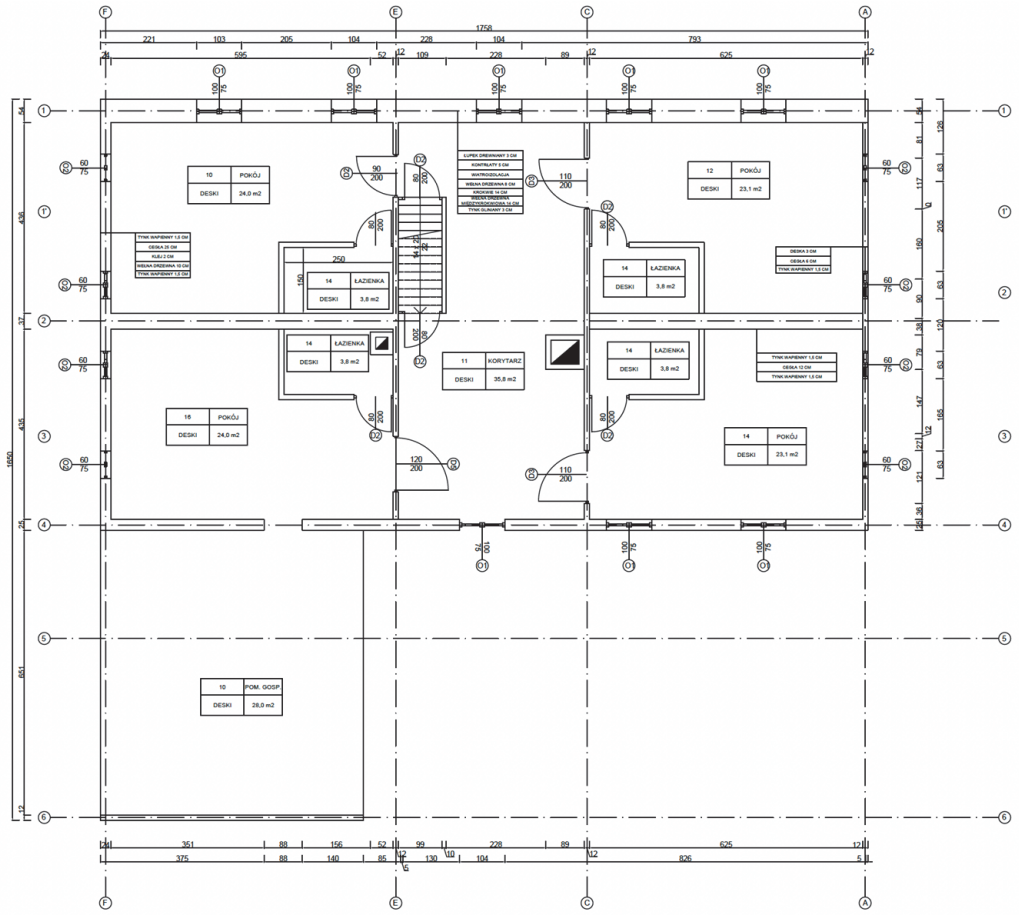


Fig. 11. Second floor after renovation

Source: own work.

Proposed technical solutions

1. Terrain regrading and an offset drainage perimeter around the building

To prevent capillary rise of moisture through lime mortar in the sandstone foundation walls, geotechnical interventions are necessary to reduce water ingress. It is recommended to implement an offset drainage perimeter that redirects groundwater away from the structure. Installing drainage directly adjacent to the foundation walls would be inappropriate due to the absence of both vertical and horizontal waterproofing layers. Excavating the foundation externally to install vertical insulation would introduce two key risks: first, the formation of a capillary chimney allowing water ingress from beneath and internally; second, disturbing the consolidated soil adjacent to the foundation, increasing its porosity and moisture absorption. Additionally, lowering the terrain on the eastern side and installing road drainage alongside the building will mitigate water runoff from the hillside, which currently contributes to the flooding and degradation of foundation walls.

2. Installation of a horizontal damp-proof course between the foundation and the ground floor walls

Several methods are available for retrofitting a horizontal damp-proof course in existing buildings. Common techniques include:

– Mechanical method. Wall undercutting involves cutting through the junction between the wall and foundation using guide rail saws in a staged manner to preserve structural integrity. The gap is filled with waterproofing materials such as bituminous felt, PE/HDPE/PVC membranes, steel plates, or epoxy resin sheets. The insulation is then wedged in place, and the remaining space is filled with mortar. While durable and easy to inspect, this method is labour-intensive and invasive, with potential risks of wall cracking or settlement.
– Chemical injection methods. Injection refers to saturating the masonry cross-section with a substance that functions by one or more of the following mechanisms: blocking the capillary network, narrowing capillaries to prevent capillary action, hydrophobising the capillary walls, or a combination of the above (Monczynski, Ksit & Szymczak-Graczyk, 2019). Examples of methods using the above mechanisms are presented in Table 1.

Table 1. Chemical injection methods

Method	Method description
Crystalline injection	This technique involves drilling two horizontal rows of holes at the wall base (10–15 cm spacing, to a depth of 70% of the wall thickness), which are then filled with a mixture of portland cement, silicates, crystallisation activators, and sealing/plasticising agents. The injected material is drawn upwards by capillarity and crystallises, blocking the pores and halting vertical moisture migration. The method is minimally invasive and applicable to diverse wall types, though it lacks direct control over the efficacy and requires several weeks for full crystallisation. It was developed by Polish engineer Dr Wojciech Nawrot.
Hydrophobic injection	Based on silane or siloxane compounds, this method imparts hydrophobic properties to capillary surfaces without blocking them. Liquid water movement is prevented while vapour permeability is maintained, preserving wall breathability.
Thermal injection	An extension of crystalline/hydrophobic injection, this method incorporates thermal ventilation devices into the drilled holes, drying the wall to 4% moisture content before injecting. This accelerates drying, reduces efflorescence, and improves performance.
Pressure resin injection	Uses pressurised polyurethane, epoxy, or acrylic resins to fill pores and capillaries. This rapid method is effective regardless of initial wall dampness but may worsen structural deterioration in highly degraded masonry.

Source: own work.

– Electrokinetic method (electroosmosis). Electrodes embedded in walls and the soil alter the direction of water flow via electric current. Its effectiveness depends heavily on material composition, humidity, and pH, with mixed results reported in the literature. A known side effect is salt accumulation in walls (Franzoni, 2018).

3. Drying of ground-floor walls

After installing a horizontal damp-proof barrier, the next step is drying the damp walls. This long-term process depends on the moisture level and wall thickness. First, the extent of moisture penetration must be determined, including inside the wall section. Then, plaster should be removed up to 1 m above the damp line. Available drying methods include:

– Natural drying. Ventilation supports surface evaporation. This weather-dependent, slow process can take years. The application of porous renovation plasters helps absorb salt efflorescence caused by evaporating moisture.
– Artificial drying. Typically involves heated air and the use of condensation or adsorption dehumidifiers. An alternative is microwave drying, which heats walls to ~80°C, enabling fast and deep moisture removal. Microwaves also have a biocidal effect, making it a recommended solution.

4. Internal insulation

To preserve the building's original form and local character, interior wall insulation is proposed. A primary concern is relocating the dew point deeper into the wall, potentially raising internal humidity and causing condensation behind the insulation. Two main systems are used:
– Vapour-open systems. These systems allow moisture migration and evaporation. Common materials include wood-fibre or calcium-silicate boards, attached using full-surface adhesive to prevent voids. Finishes must be vapour-permeable (e.g. clay or lime plaster, mineral paints), making it a recommended solution.
– Vapour-closed systems. These systems use vapour barriers to prevent moisture ingress into the insulation layer. Materials include PIR, PUR, or EPS boards. Non-permeable interior finishes (e.g. gypsum board, cement plaster) may be used. However, the system is highly sensitive to execution errors: any breach in the vapour barrier can cause moisture accumulation and microbial growth.

Both systems present thermal bridging risks at junctions with other building elements. Solutions include adding 30–40 cm insulation strips on adjoining walls and floors. Mounting fixtures requires special considerations to avoid damaging the vapour barrier. Despite these challenges, internal insulation improves thermal comfort by keeping internal surfaces warm. Moreover, structural considerations for new wooden floor beams should take into account insulating the building from the inside. When installing internal insulation, increased wall moisture may adversely affect wooden floor beams embedded in the masonry, leading to wetting, freezing, and biological decay. Preventative measures include using steel or concrete spacers and leaving an air gap around beam ends to facilitate drying.

5. Restoration of the historical roofing

Due to the structural degradation of the upper floors and roof, complete replacement of the timber structure is necessary. Originally, the building had a wooden shingle roof, which may be restored with good thermal outcomes. This breathable roofing system must be installed on a lath and counter-lath grid, with a wind membrane atop vapour-open wood-fibre boards fixed to rafters. Inter-rafter spaces are also filled with insulation. The interior finish should be fibre-permeable to facilitate drying and maintain indoor air quality. Phosphorus-based fire retardants may be used to enhance fire safety and reduce smoke and heat emission (Park, Lee, Kang, Lee & Shim, 2020).

6. Heating system replacement

Currently, the building is partially heated via a solid-fuel stove in the kitchen with a water heat exchanger and a tiled top. This system is inefficient, labour-intensive, and causes thermal bridging due to unheated zones. To improve energy performance, reduce operating costs, and minimise environmental impact, a new system is proposed:
– Ground source heat pump (GSHP). GSHPs utilise underground glycol-filled collectors (horizontal or vertical) to extract heat. Glycol is vapourised in an evaporator, then compressed to increase

its temperature. The hot gas heats water via a condenser. This highly efficient system achieves a coefficient of performance (COP) of up to 4.9 in winter and 2.3 in summer (Desideri, Sorbi, Arcioni & Leonardi, 2011).

– Heat recovery ventilation (HRV). HRV systems recover heat from exhaust air, supplementing the GSHP. Over time, the ground temperature around the collector drops, reducing efficiency. Supplementing the glycol loop with heat from exhaust air stabilises ground temperature and enhances system performance (Ya-Su, Fahlen & Lindholm, 2007).
– Low-temperature underfloor heating. In the case of heating the building using a ground-source heat pump, low-temperature heating systems are preferable due to the increased efficiency of the heat pump operating at lower supply temperatures. Although underfloor heating systems have higher thermal inertia, they enable an even distribution of heat throughout the building volume. Moreover, they help maintain the temperature of wooden floor structures, thereby preventing moisture accumulation in the beams resting on internally insulated walls.
– Photovoltaic installation. By supplying the heat pump with electricity generated by photovoltaic (PV) panels, it is possible to achieve up to a 40% reduction in life-cycle operating costs and a 30% decrease in carbon dioxide emissions (Wang, Quan, Zhao, Rosengarten & Mojiri, 2025). In order to preserve the architectural and historical integrity of the renovated building, it is proposed that the PV panels be installed on the roof of the adjacent barn. Importantly, the southern slope of the barn roof is not visible from the street, minimising visual impact. The system's capacity should be sized appropriately to meet the energy demands of the installations described above.
– Energy storage system. To fully capitalise on the potential of the photovoltaic installation, the integration of an energy storage system (battery bank) is recommended. This would allow the surplus energy generated during the day to be stored and used during nighttime hours. Such a solution contributes to further reductions in the consumption of primary energy required for the operation of the building.

RESULTS

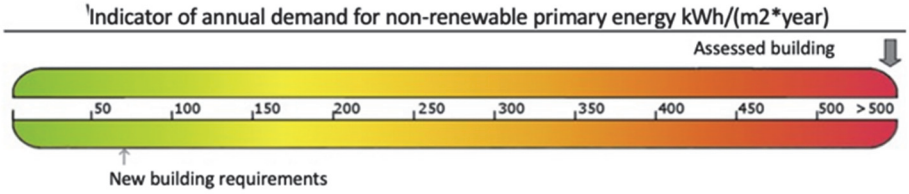
Energy modelling and performance improvement

The building was modelled using ArCADia-THERMOCAD software developed by ArCADiasoft. Utilising specialised energy performance modelling software enables comprehensive energy analysis by accounting for building geometry, material properties, and thermal bridging.

As a result of the proposed thermal retrofitting measures, the building's primary energy demand was reduced from 878.9 $kWh \cdot m^{-2} \cdot year^{-1}$ to 54.6 $kWh \cdot m^{-2} \cdot year^{-1}$ – a more than sixteenfold decrease (Tables 2–3). Following the renovation, this over one-hundred-year-old structure now meets contemporary energy performance standards while offering improved indoor comfort and long-term operational cost savings for future users.

Equally significant is the elimination of the solid fuel boiler, which previously contributed to the emission of harmful gases and particulate matter detrimental to human health. The integration of renewable solar energy systems – coupled with energy storage capabilities – further reduces reliance on primary energy sources and enhances the sustainability of the building.

Table 2. Assessment of the energy performance of the building before renovation

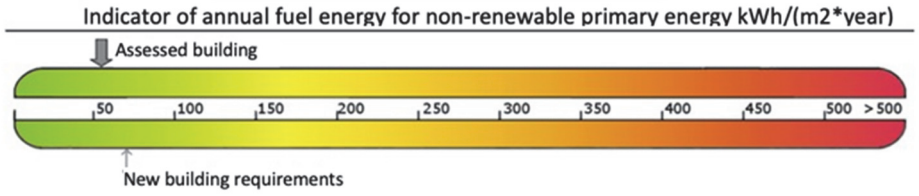
Building under review			
Building Type 2)	Residential		
Purpose of the building 3)	House		
Building address	57-313 Stary Wielisław 183		
Building referred to in Article 3(2) of the Act 4)	No		
Year of completion of the building 5)	1910		
Method for determining energy performance 6)	calculation method for the accepted mode of use and standard climatic conditions		
Area of rooms with adjustable air temperature (heated or cooled area) Af [m2] 7)	294.10 m2		
Usable area [m2]	294,10 m2		
Valid until (yyyy-mm-dd) 8)	15.06.2035		
A weather station according to which data is determined 9)	Kłodzko		
Assessment of the energy performance of the building 10)			
Energy Performance Indicators	**Building under review**	**Requirements for a new building according to the technical and construction regulations 11)**	
Indicator of annual demand for useful energy	EU= 382.8 kWh/(m2·year)		
Indicator of annual final energy demand 12)	EK= 798.1 kWh/(m2·year)		
Indicator of annual demand for non-renewable primary energy 12)	EP= 878.9 kWh/(m2·year)	EP= 70.0 kWh/(m2·year)	
Unit CO2 emissions	ECO2= 0.28244 t CO2/(m2·year)		
Share of renewable energy sources in annual final energy demand	UOZE= 0.00 %		
			
Calculated annual amount of energy carrier or energy consumed by the building13)			
Technical system	**Type of energy carrier or energy**	**Amount of energy carrier or energy**	**Unit/(m2·year)**
Heating	Local energy generation in a building - Hard coal	108,15	kg/(m2·year)
	System power grid - Electricity	0,57	kWh/(m2·year)
Domestic hot water preparation	Local energy generation in a building - Hard coal	20,19	kg/(m2·year)
	System power grid - Electricity	0,11	kWh/(m2·year)
Cooling	--	--	--
Built-in lighting system 11)	--	--	--

Source: own work.

Table 3. Assessment of the energy performance of the building after renovation

Building under review		
Building Type 2)	Residential	
Purpose of the building 3)	House	
Building address	57-313 Stary Wielisław 183	
Building referred to in Article 3(2) of the Act 4)	No	
Year of completion of the building 5)	1910	
Method for determining energy performance 6)	calculation method for the accepted mode of use and standard climatic conditions	
Area of rooms with adjustable air temperature (heated or cooled area) Af [m2] 7)	294.10 m2	
Usable area [m2]	294.10 m2	
Valid until (yyyy-mm-dd) 8)	15.06.2035	
A weather station according to which data is determined 9)	Kłodzko	

Assessment of the energy performance of the building 10)		
Energy Performance Indicators	**Building under review**	**Requirements for a new building according to the technical and construction regulations 11)**
Indicator of annual demand for useful energy	EU= 176.0 kWh/(m2·year)	
Indicator of annual final energy demand 12)	EK= 93.2 kWh/(m2·year)	
Indicator of annual demand for non-renewable primary energy 12)	EP= 54.6 kWh/(m2·year)	EP= 70.0 kWh/(m2·year)
Unit CO2 emissions	ECO2= 0.00738 t CO2/(m2·year)	
Share of renewable energy sources in annual final energy demand	UOZE= 52.71 %	



Calculated annual amount of energy carrier or energy consumed by the building13)			
Technical system	**Type of energy carrier or energy**	**Amount of energy carrier or energy**	**Unit/(m2·year)**
Heating	On-site energy generation in a building - Solar energy	34,75	kWh/(m2·year)
	System power grid - Electricity	16,95	kWh/(m2·year)
Domestic hot water preparation	On-site energy generation in a building - Solar energy	36,59	kWh/(m2·year)
	System power grid - Electricity	4,88	kWh/(m2·year)
Cooling	--	--	--
Built-in lighting system 11)	--	--	--

Source: own work.

Although calculations based on a computer model are precise and reliable, high-quality, structured data is crucial. There is also a risk of oversimplification and making too many assumptions, which can lead to a loss of accuracy. This can apply to historic buildings, which are made from various materials and can be surprisingly heterogeneous.

Effectiveness of the thermal modernisation

To assess the effectiveness of the planned thermal modernisation, the analysis of thermal resistance of external partitions and roof layers was performed (Tables 4–7).

Table 4. Layers of external wall before modernisation

Layer	Material	Dimension [m]	Heat conduction coefficient (λ) [-]	Thermal resistance [$m^2 \cdot K \cdot W^{-1}$]
1	lime plaster	0.015	0.700	0.021
2	solid brick	0.680	0.780	0.872
3	lime plaster	0.015	0.700	0.021

Source: own work.

Table 5. Layers of external wall after modernisation

Layer	Material	Dimension [m]	Heat conduction coefficient (λ) [-]	Thermal resistance [$m^2 \cdot K \cdot W^{-1}$]
1	lime plaster	0.015	0.700	0.021
2	wood-fibre boards	0.100	0.038	2.632
3	solid brick	0.680	0.780	0.872
4	lime plaster	0.015	0.700	0.021

Source: own work.

Table 6. Layers of the roof before modernisation

Layer	Material	Dimension [m]	Heat conduction coefficient (λ) [-]	Thermal resistance [$m^2 \cdot K \cdot W^{-1}$]
1	asbestos boards	0.020	0.700	0.029

Source: own work.

Table 7. Layers of the roof after modernisation

Layer	Material	Dimension [m]	Heat conduction coefficient (λ) [-]	Thermal resistance [$m^2 \cdot K \cdot W^{-1}$]
1	lime plaster	0.015	0.700	0.021
2	wood-fibre boards	0.220	0.038	5.789
5	foil	0.002	0.300	0.007
6	air void	0.050	×	0.180
7	wooden roofing	0.030	0.160	0.188

Source: own work.

As a result of the thermal modernisation, the heat transfer coefficient for the external wall has decreased by a factor of over three, and by over 36 for the roof. Results like this are excellent and mean that far more energy is being saved.

DISCUSSION

This study aimed to reconcile contemporary energy efficiency requirements with the conservation of architectural heritage by employing context-sensitive and technically appropriate interventions. The analysis demonstrates that, when guided by a carefully planned and integrated strategy, it is possible to attain a high level of energy performance without undermining the historical character or cultural significance of the building.

Importantly, the renovation of historic and traditional architecture plays a crucial role in preserving cultural heritage and identity. Historic buildings serve not only as material artefacts of architectural and construction practices but also as markers of the sociocultural, economic, and environmental narratives of their time. Their continued existence enables intergenerational transmission of knowledge, values, and aesthetics that might otherwise be lost (Nassir, 2020). In regions with complex and often turbulent histories – such as many areas of Central and Eastern Europe – heritage preservation becomes especially significant. In the face of global homogenisation and the proliferation of standardised architectural forms, the conservation and adaptive reuse of historic buildings offer a means of maintaining local distinctiveness and cultural continuity (Nguyen & Khuat, 2024).

Nevertheless, the process of renovating historic buildings is not without challenges. Renovators must often navigate conflicting priorities between improving energy performance and adhering to heritage preservation standards. Regulatory frameworks may impose restrictions that limit the extent to which energy upgrades can be implemented, while technical difficulties associated with integrating modern systems into old structures further complicate renovation efforts. As Mazzarella (2015) notes, a balanced and context-sensitive approach is required – one that recognises the value of cultural heritage while striving to meet contemporary environmental performance goals.

CONCLUSIONS

In the context of rapid advancements in building technologies and mounting global pressure to reduce the carbon footprint of the construction sector, the renovation of historic buildings has emerged as a key challenge for engineers, architects, and conservation specialists. This case study demonstrates that, with a carefully planned and context-sensitive approach, it is possible to achieve high energy performance standards without compromising the architectural integrity or cultural value of heritage structures.

The integration of vapour-open (diffusion-permeable) materials and assemblies ensured balanced moisture transfer through the building envelope, thereby preventing the accumulation of condensation, protecting the structural integrity of timber-framed elements, and promoting a healthy indoor microclimate. At the same time, the implementation of a low-temperature underfloor heating system in conjunction with a ground-source heat pump, mechanical ventilation with heat recovery, and a photovoltaic installation – including an energy storage system – enabled a radical reduction in primary energy demand. These interventions not only enhance user comfort but also eliminate local emissions from fossil fuel combustion, contributing to cleaner air and improved public health.

The use of advanced energy modelling software (ArCADia-THERMOCAD) allowed for a precise assessment of thermal performance, taking into account geometric features, material properties, and thermal bridges. The result was a dramatic reduction in the building's primary energy demand – from 878.9 $kWh \cdot m^{-2} \cdot year^{-1}$ to 54.6 $kWh \cdot m^{-2} \cdot year^{-1}$ – without altering its external appearance or internal spatial

character. As the house is heated just partially, using solid fuel and tiled stoves, there is no reliable data on its actual energy consumption.

This example reinforces the idea that appropriately executed energy retrofitting of historic structures does not conflict with their conservation; on the contrary, it can reinforce their value. Through the extension of the building's life span – adaptation to contemporary functional and environmental standards, and restoration of its original aesthetic qualities – the renovation contributes meaningfully to the cultural and material sustainability of the built environment.

In a broader context, such interventions align with the principles of sustainable development. They reduce the demand for new construction, conserve material and cultural resources, and promote circular economy strategies within the building sector. As heritage buildings represent a significant share of the existing building stock, their energy-efficient adaptation is essential not only for climate goals but also for maintaining the continuity of place, identity, and memory in architectural heritage.

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Authors' contributions

Conceptualisation: Ł.C. and A.N.; methodology: A.N.; validation: A.N.; formal analysis: Ł.C.; investigation: Ł.C.; resources: Ł.C.; data curation: Ł.C.; writing – original draft preparation: Ł.C.; writing – review and editing: A.N.; visualisation: Ł.C.; supervision: A.N.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Alarcón, F. (2023). Four Seasons House | Casa cuatro estaciones. *Arq*, *2023* (113), 66–71. https://doi.org/10.4067/S0717-69962023000100066

Benke, B., Lewis, M., Carlisle, S., Huang, M. & Simonen, K. (2022). *Developing an Embodied Carbon Policy Reduction Calculator Quantifying the embodied emissions reduction potentials of city policies*. Retrived from: https://carbonleadershipforum.org/our-sponsors/ [accessed: 01.06.2025].

Darko, A., Weerasinghe, L. N. K., Chan, A. P. C. & Wu, L. (2025). Partial Least Squares Structural Equation Modeling of Challenges to Existing Residential Building Net Zero Carbon Retrofitting. *Journal of Construction Engineering and Management*, *151* (8). https://doi.org/10.1061/JCEMD4.COENG-16471

Desideri, U., Sorbi, N., Arcioni, L. & Leonardi, D. (2011). Feasibility study and numerical simulation of a ground source heat pump plant, applied to a residential building. *Applied Thermal Engineering*, *31* (16), 3500–3511. https://doi.org/10.1016/j.applthermaleng.2011.07.003

Ferreira, M., Almeida, M. & Rodrigues, A. (2017). Impact of co-benefits on the assessment of energy related building renovation with a nearly-zero energy target. *Energy and Buildings*, *152*, 587–601. https://doi.org/10.1016/j.enbuild.2017.07.066

Fleur, L. L., Rohdin, P. & Moshfegh, B. (2019). Energy renovation versus demolition and construction of a new building – a comparative analysis of a Swedish multi-family building. *Energies*, *12* (11). https://doi.org/10.3390/en12112218

Franzoni, E. (2018). State-of-the-art on methods for reducing rising damp in masonry. *Journal of Cultural Heritage*, *31*, S3–S9. https://doi.org/10.1016/j.culher.2018.04.001

Gao, T. & Li, H. (2008). Assessment of energy-saving potential based on the renovation of existing residential buildings in cold zones of China. *38th International Conference on Computers and Industrial Engineering 2008*, *3*, 2302–2307.

Gavu, E. K. & Peiser, R. B. (2024). Embodied Carbon and the Nuances in Office-to-Residential Conversions. *Sustainability Switzerland*, *16* (7). https://doi.org/10.3390/su16072711

Gillett, W. B., Kalogirou, S. A., Morthorst, P. E., Norton, B. & Ornetzeder, M. (2025). Perspectives on decarbonisation of existing buildings in Europe. *Renewable Energy*, *242*. https://doi.org/10.1016/j.renene.2025.122490

Hasik, V., Escott, E., Bates, R., Carlisle, S., Faircloth, B. & Bilec, M. M. (2019). Comparative whole-building life cycle assessment of renovation and new construction. *Building and Environment*, *161*. https://doi.org/10.1016/j.buildenv.2019.106218

Huo, T., Ma, Y., Cai, W., Liu, B. & Mu, L. (2021). Will the urbanization process influence the peak of carbon emissions in the building sector? A dynamic scenario simulation. *Energy and Buildings*, *232*. https://doi.org/10.1016/j.enbuild.2020.110590

Liao, H., Ren, R. & Li, L. (2023). Existing Building Renovation: A Review of Barriers to Economic and Environmental Benefits. *International Journal of Environmental Research and Public Health*, *20* (5). https://doi.org/10.3390/ijerph20054058

Lucuik, M., Huffman, A., Trusty, W. & Prefasi, A. (2010). *The greenest building is the one that is never built: A life-cycle assessment study of embodied effects for historic buildings*. Paper presented at the Thermal Performance of the Exterior Envelopes of Whole Buildings – 11th International Conference.

Martinaitis, V., Rogoža, A. & Bikmaniene, I. (2004). Criterion to evaluate the 'twofold benefit' of the renovation of buildings and their elements. *Energy and Buildings*, *36* (1), 3–8. https://doi.org/10.1016/S0378-7788(03)00054-9

Mastrucci, A., Marvuglia, A., Benetto, E. & Leopold, U. (2020). A spatio-temporal life cycle assessment framework for building renovation scenarios at the urban scale. *Renewable and Sustainable Energy Reviews*, *126*. https://doi.org/10.1016/j.rser.2020.109834

Mazzarella, L. (2015). Energy retrofit of historic and existing buildings. the legislative and regulatory point of view. *Energy and Buildings*, *95*, 23–31. https://doi.org/10.1016/j.enbuild.2014.10.073

Monczynski, B., Ksit, B. & Szymczak-Graczyk, A. (2019). Assessment of the Effectiveness of Secondary Horizontal Insulation Against Rising Damp Performed by Chemical Injection. *IOP Conference Series: Materials Science and Engineering*, *471* (5). https://doi.org/10.1088/1757-899X/471/5/052063

Nassir, M. (2020). A look at the erroneous restoration of the historical kasbah of agadir, Morocco. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences – ISPRS Archives*, *54* (M–1), 1111–1115. https://doi.org/10.5194/isprs-archives-XLIV-M-1-2020-1111-2020

Nguyen, N. T. & Khuat, N. T. (2024). Sustainable Preservation of Vernacular Architecture for Enhancing Urban Cultural Welfare in Vietnamese Ethnic Minority Communities. *FWU Journal of Social Sciences*, *18* (4), 127–139. https://doi.org/10.51709/19951272/Winter2024/9

O'Reilly, K. M. A., Mclaughlin, A. M., Beckett, W. S. & Sime, P. J. (2007). Asbestos-related lung disease. *American Family Physician*, *75* (5), 683–690.

Panorama of Altwilmsdorf [photography] (n.d.). Polska-org.pl. Retrieved from: https://polska-org.pl/4886275,foto.html?idEntity=504631 [accessed: 01.06.2025].

Park, S.-H., Lee, M., Kang, E.-C., Lee, S.-M. & Shim, K. (2020). Manufacture of Semi Non-combustible Wood-fiber Insulation Boards by Inorganic Fire-retardant Treatment. *BioResources*, *15* (4), 8235–8248. https://doi.org/10.15376/biores.15.4.8235-8248

Passoni, C., Caruso, M., Felicioni, L. & Negro, P. (2024). The evolution of sustainable renovation of existing buildings: from integrated seismic and environmental retrofitting strategies to a life cycle thinking approach. *Bulletin of Earthquake Engineering*, *22* (13), 6327–6357. https://doi.org/10.1007/s10518-024-01991-0

Postcard from Altwilmsdorf type Gruss [postcard] (n.d.). Polska-org.pl. Retrieved from: https://polska-org.pl/5349048,foto.html?idEntity=504631 [accessed: 01.06.2025].

Rybak-Niedziółka, K., Starzyk, A., Łacek, P., Mazur, Ł., Myszka, I., Stefańska, A., Kurcjusz, M., Nowysz, A. & Langie, K. (2023). Use of Waste Building Materials in Architecture and Urban Planning – A Review of Selected Examples. *Sustainability Switzerland*, *15* (6). https://doi.org/10.3390/su15065047

Serrano, T., Kampmann, T. & Ryberg, M. W. (2022). Comparative Life-Cycle Assessment of restoration and renovation of a traditional Danish farmer house. *Building and Environment*, *219*. https://doi.org/10.1016/j.buildenv.2022.109174

Starzyk, A., Rybak-Niedziółka, K., Nowysz, A., Marchwiński, J., Kozarzewska, A., Koszewska, J., Piętocha, A., Vietrova, P., Łacek, P., Donderewicz, M., Francke, B. & Podlasek, A. (2024). New Zero-Carbon Wooden Building Concepts: A Review of Selected Criteria. *Energies*, *17* (17). https://doi.org/10.3390/en17174502

Wang, Y., Quan, Z., Zhao, Y., Rosengarten, G. & Mojiri, A. (2025). Techno economic analysis of integrating photovoltaic-thermal systems in ground-source heat pumps for heating-dominated regions. *Applied Energy*, *377*. https://doi.org/10.1016/j.apenergy.2024.124677

Weerasinghe, L. N. K., Darko, A., Chan, A. P. C., Blay, K. B. & Edwards, D. J. (2024). Measures, benefits, and challenges to retrofitting existing buildings to net zero carbon: A comprehensive review. *Journal of Building Engineering*, *94*. https://doi.org/10.1016/j.jobe.2024.109998

Ya-Su, Z., Fahlen, P. & Lindholm, T. (2007). Performance and optimization for a ground-coupled liquid loop heat recovery ventilation system. *Journal of Donghua University English Edition*, *24* (6), 749–755.

OCENA WPŁYWU KOMPLEKSOWEJ TERMOMODERNIZACJI NA EFEKTYWNOŚĆ ENERGETYCZNĄ BUDYNKU ZABYTKOWEGO: STUDIUM PRZYPADKU DOMU NA DOLNYM ŚLĄSKU, POLSKA

STRESZCZENIE

Celem niniejszej pracy była ocena wpływu kompleksowej modernizacji termicznej na efektywność energetyczną zabytkowego budynku mieszkalnego z XIX wieku. Główna hipoteza zakładała, że możliwe jest osiągnięcie znacznego zmniejszenia zapotrzebowania na energię pierwotną bez naruszania integralności architektonicznej i historycznej budynku. Badania przeprowadzono w formie studium przypadku istniejącej konstrukcji zabytkowej położonej w województwie dolnośląskim w Polsce. Proponowana strategia modernizacji obejmowała wdrożenie gruntowej pompy ciepła, wentylacji mechanicznej z odzyskiem ciepła, niskotemperaturowego ogrzewania podłogowego, i paneli fotowoltaicznych oraz zastosowanie naturalnych, paroprzepuszczalnych materiałów izolacyjnych zgodnych z zasadami otwartości dyfuzyjnej. Analiza porównawcza certyfikatów charakterystyki energetycznej budynku wykazała znaczne zmniejszenie zapotrzebowania na energię pierwotną (z 878,9 kWh·m^{-2}·rok^{-1} do 54,6 kWh·m^{-2}·rok^{-1}), co tym samym potwierdziło hipotezę badawczą. Wyniki te podkreślają możliwość pogodzenia współczesnych wymagań dotyczących efektywności energetycznej z ochroną architektury zabytkowej, pod warunkiem zastosowania rozwiązań dostosowanych do swoistych cech obiektu i odpowiednich pod względem technologicznym.

Słowa kluczowe: modernizacja termiczna, charakterystyka energetyczna budynku, renowacja budynku, budynek historyczny

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ORIGINAL PAPER

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MORE SUSTAINABLE THAN IT SEEMS – THE SOCIAL SUSTAINABILITY OF WARSAW'S MULTI-RESIDENTIAL PREFABRICATED HOUSING FROM THE 1970s AND 80s

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ABSTRACT

After the fall of communism in 1989, Warsaw's large-panel housing estates became an unwanted legacy of the previous era. Frequently, they were characterised by poor quality of workmanship, deficiencies in the surrounding infrastructure and the monotony of the urban space. However, in the second decade of the 21st century, their potential has become increasingly appreciated. Unlike other European capitals, large housing estates from the 1970s and 80s have not become isolated poor districts of the city, but rather an integrated part of Warsaw with a socio-economically diverse community. This research analyses this phenomenon to explain how spaces that were doomed to failure 30 years ago can inform building a sustainable city. Despite the several flaws in the large-panel estates, they are characterised by features that are currently unattainable, such as apartment size, layout and public spaces. The way these estates function today forces us to consider sources of positive social reception and differences in relation to housing developments implemented under the current free market conditions.

Keywords: panel building, multifamily housing, social sustainability, Poland

INTRODUCTION

Over the last decades, it has been observed that large-scale multifamily housing projects have failed to address the housing shortage and growing socio-economic challenges in Europe. This paper investigates selected prefabricated housing projects in Warsaw, Poland, that seem to be surviving well despite the changing social environment. This investigation aims to provide insights into the drivers behind the survival of such schemes and intends to inform decision-making, especially in other European countries facing housing crises and where multiple deprivation is frequently linked to urban form (Vassileva-Karagyozova & Wood, 2012).

Large-scale prefabrication technology in housing construction in Poland was driven by the post-WWII demographic boom and resulted from the acute shortage of housing. It started in the early 1960s, when major parts of larger cities were subjected to central government planning. This is when the pre-war left-wing idea of social estates was turned into the idea of workers' estates or, more realistically, into the minimum existence housing (Kiciński, 2004). The central plans determined the housing standards and models, and prefabrication has

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become the solution for rapid housing production. By now, there are 4 million prefabricated apartments making up some 25% of all housing in Poland (Kaźmierczak, 2021). These planned-from-scratch large-scale urbanisation projects followed the theoretical concepts of the Congrès Internationaux d'Architecture Moderne (CIAM). Hence, these developments were naturally similar to what has been developed in the western side of the Iron Curtain. In Poland, prefabricated housing evolved from using predominantly large block technologies in the early 1970s to large panels dominating from the mid-1970s till the late 1980s (Radziszewska-Zielina & Gleń, 2014).

The reception of prefabricated housing was mixed, and despite design similarities, these developments instigated different social and cultural reactions, leading to the long-term success or failure of these social experiments (Crowley & Reid, 2002). In developed economies, many of these estates have not withstood the test of time, and some were even completely demolished, like Pruitt-Igoe in St. Louis, the United States (Jencks, 1977; Gąsowska-Kramarz, 2019) and Les Minguettes in Lyon, France (Blanc & Stebe, 2004) or their existence was challenged, like the *Plattenbau* in Berlin (van der Hoorn, 2004). Contrary to that in Poland, despite the bleak predictions (Vassileva-Karagyozova & Wood, 2012), prefabricated multifamily block estates still seem to serve their inhabitants well and are not a major driver for deprivation, e.g. in Kraków and Jędrzejów "these buildings have obtained a satisfactory social rating and can certainly serve their residents well for many years" (Radziejowska & Sobotka, 2021, p. 106).

To explain the phenomenon of social survival of such schemes, this research identified examples of large-scale prefabricated housing schemes in Warsaw, which today still address the purpose they were built for. We then look into its urban structure, architectural form, amenities and other parameters to explain how they perform in terms of their social sustainability.

The rest of this paper is structured as follows: The next section, *Material and methods,* describes our methodological approach. *Social sustainability and social value in housing* explores the social, economic, and political justification for large-scale prefabricated technology in housing projects developed in the 1970s and 80s. *The construction of prefabricated housing estates in Warsaw in the 1970s and 80s* looks into the urban and architectural principles to achieve the social aims of these projects. *The current state of prefabricated housing estates in Warsaw* provides an overview of our methodological approach. The paper ends with conclusions suggesting relying on these schemes as spaces that not only provide accommodation, but more importantly, deliver social value.

MATERIAL AND METHODS

This paper uses qualitative research methods, including, in the first stage, archival research of the literature discussing social value and the historical context (Krippendorff, 2019), as well as visual landscape surveys of Warsaw's housing estates from the 1970s and 80s, and in the second stage, a comparative analysis of 1970s and 80s stock versus post-1989 housing developments. Thus, the first stage focuses on the sustainability features of the 1970s and 80s residential estates. These are not narrow case studies, as the main objective is to capture the general phenomena of well-functioning housing estates within the structure of the entire city of Warsaw. The second stage, aiming to situate the studied architecture and urbanism of prefabricated estates, provides a critical reflection on the current state of 1970s and 80s residential estates in the context of their social sustainability and social value in relation to wider changes in the city driven by the post-1989 housing stock. This approach allows for interpreting the architecture in different ways, well beyond pure environmental sustainability.

Although the title of this paper suggests that Warsaw's prefabricated housing estates built before 1989 would have been sustainable, their production methods and characteristic urban planning were far from what we would nowadays refer to as sustainable developments. The key factor in this case is the very fact of their presence within the much larger structure of the city. Avoiding their demolition and ensuring their efficient functioning

in harmony with other parts of the city built after 1989 seems to be the greatest challenge. Hence, this research explores the concept of sustainable development and presents perspectives on how selected large-scale estates function within the capital city. The selection of large-scale estates considered their characteristics such as: (1) location in Warsaw, (2) period of construction (1970s and 80s), (3) size of the developed area, and (4) number of apartments. While the first and second criteria served to identify specific estates, the third and fourth criteria were used to identify estates of distinctive characteristics to illustrate various perspectives on their social sustainability and, where applicable, changes since their completion (Fig. 1, Table 1).

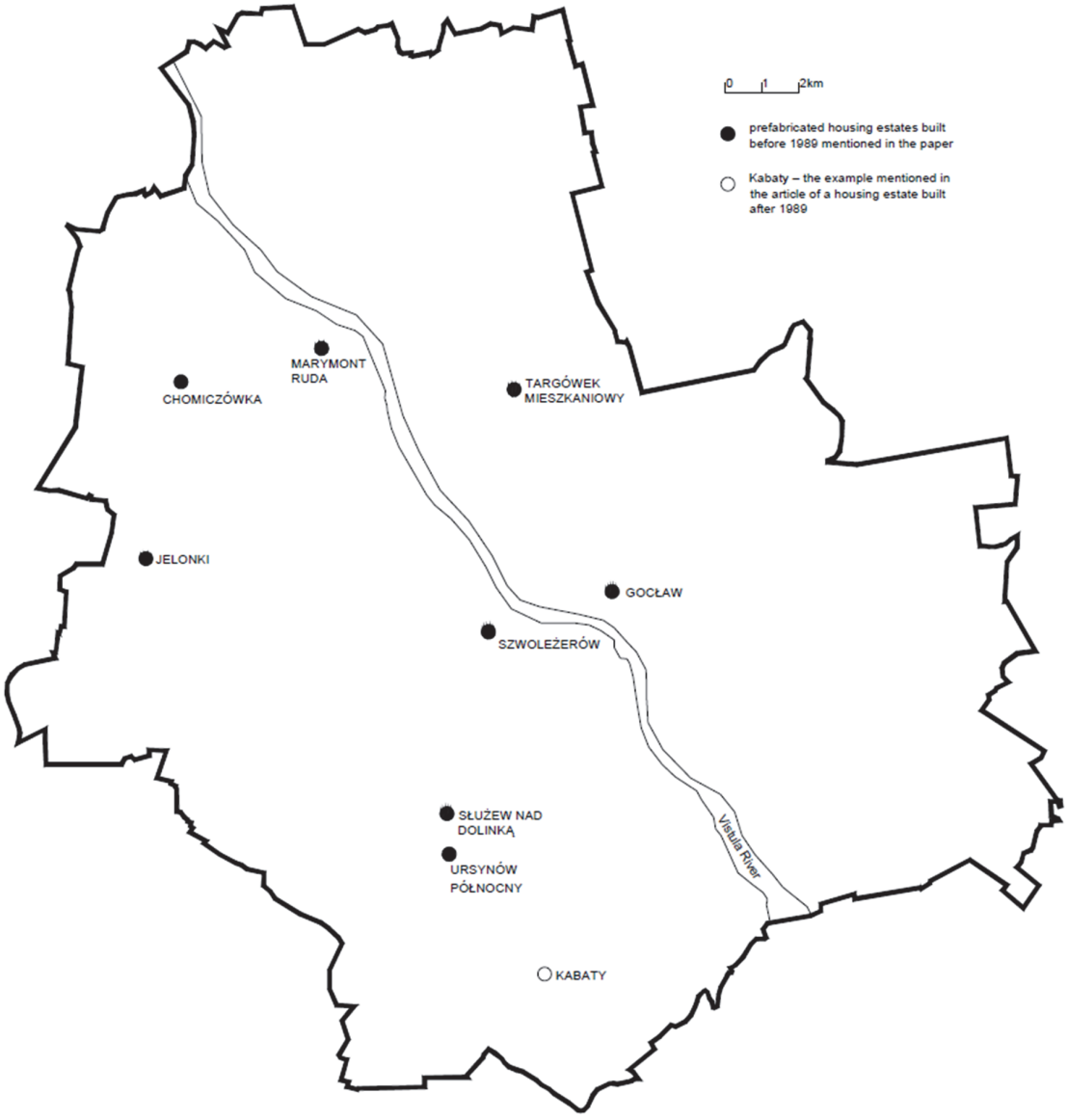


Fig. 1. Location of analysed housing estates

Source: own work.

Table 1. Analysed housing estates

Residential estate	Development period[a]	Area [ha]	Number of apartments
Marymont Ruda	late 1970s	36	~3,200
Chomiczówka	1975–1980	103	~5,600
Jelonki	1974–1977	51	~4,400
Szwoleżerów	1971–1974	4	~450
Służew nad Dolinką	1975–1979	42	~5,400
Ursynów Północny	1975–1978	195	~9,600
Kabaty	1987–early 1990s (majority of buildings) and 2000–2002	13	~2,500
Targówek Mieszkaniowy	1974–1978	78	~6,400
Gocław	1976–1979 (first section)–1990 (last building)	119	~11,000

[a]Where no further details were provided, the development period relates to the period when the majority of residential buildings were completed. In the 1970s and 80s, social infrastructure in large housing estates was frequently completed towards the end of construction of the residential buildings or within a few years after.

Source: Burczynski (2017), Żylski (2019), Orchowska and Klimowicz (2023), Korusiewicz (2025), Spółdzielnia Mieszkaniowa "Służew nad Dolinką" (2025), Spółdzielnia Mieszkaniowa "Szwoleżerów" (2025).

SOCIAL SUSTAINABILITY AND SOCIAL VALUE IN HOUSING

Close to 30 years ago, Choguill (1994) established the multidimensionality of sustainability in housing, including ecological, economic, technological, cultural and social sustainability. Despite extensive debates over the past years, social sustainability is still subject to interpretation (Dixon, 2019), be it in the context of sustainability dimensions such as economic or environmental or in the context of place, ranging from a single building to towns or cities. The 'place' dimension has been subject to extensive research by Dempsey, Bramley, Power and Brown (2011), Woodcraft, Bacon, Caistor-Arendar and Hackett et al. (2011), and Dixon and Woodcraft (2013). A detailed account of this can be found in a paper by Dixon (2019). On the other hand, terms such as 'social' or 'community' together with 'inclusion', 'cohesion', 'equity', 'wellbeing' or simply 'safety' or 'security' are often associated with social sustainability. However, such terms are more often used in the context of new housing projects, urban regeneration, or the assessment of reasonably recent projects rather than for older stock (Khor & Abu Bakar, 2012; Wiesel et al., 2012; Dixon & Woodcraft, 2013). While many evaluation systems are in existence, each offers a slightly different focus.

Similarly, the issue of 'social value' has been subject to an intensive debate over at least the last two decades by various researchers and institutions from across disciplines such as economics, sociology and politics (Raiden, Losemore, King & Gorse, 2018). Yet still, there is some confusion about what constitutes social value. Emerson (2000) defines social value as the generation of improvements to the lives of individuals or society through resources, processes and policies. Social Enterprise UK simplifies that to "positive externalities or social, economic and environmental wellbeing above and beyond the 'core' value of the good, service or work" (Nicholls, 2023, p. 5). Many countries have their own definitions. The UK's Social Value (Public Services) Act 2012 defines it as maximisation of additional benefits beyond the benefit of the goods and services themselves.

Many researchers have attempted to quantify or at least to propose measurable parameters for social sustainability in housing, pointing out mostly the quality of the environment and other aspects such as land uses and urban design, transportation, architectural design and layout (Ding, 2008; Brandon & Lombardi, 2011; Soo Cheen & Abu Bakar, 2012; Kalfaoglu Hatipoğlu, 2017).

Given the above, various models address different perspectives. The Affordable and Socially Sustainable Housing Assessment (ASHA) tool is based on social sustainability's positive externalities, including reducing health expenses, improving employment and enterprise, improving educational outcomes, improving safety and security, increasing social capital, reducing commuting impacts, and increasing housing stability (International Finance Corporation [IFC], 2015). Bearing in mind the lack of consistency or disagreement on criteria, the ASHA tool seems to be an attempt to address both the qualitative criteria (affordability, design quality, local economy, health, safety and security) and project stages (project definition, planning and design, construction and operation) but not larger estates or self-contained urban areas (IFC, 2015). On the other hand, the Geneva UN Charter on Sustainable Housing (United Nations Economic Commission for Europe [UNECE], 2015) suggests a narrower perspective of environmental protection, economic effectiveness, social inclusion and participation, and cultural adequacy. Yet another approach is taken for the Housing Sustainability Assessment Tool (Adamec, Janoušková & Hák, 2021), which is based on four sustainability dimensions (economic, environmental, institutional and social) and three housing components (building, locality and community). Further, Kalfaoglu Hatipoğlu (2017), in the Sustainable Housing Quality Framework, adds dimensions such as needs-oriented design and participation, as well as the flexibility and diversity of buildings and apartments. However, none of these models comprehensively addresses the urban and architectural design in an intertemporal context.

There is no uniform definition of sustainable space. In construction, a sustainable built environment may sometimes be seen as an oxymoron, such as the promotion of shorter-life wooden constructions to avoid the use of fossil fuels and materials (Starzyk, Cortiços, Duarte & Łacek, 2025). On the other hand, solid (stone or brick) structures lasting for several hundred years can also be interpreted as sustainable, as exemplified by historic city centres (European Environment Agency [EEA], 2024). Similar assumptions also apply to space in a broader context. Housing estates are part of a larger urban organism that is embedded in a specific social context. Treating them in a laboratory-like manner may be misleading. The approach taken in this research, focusing on a large city, fits within social sustainability understood as "development (and/or growth) that is compatible with the harmonious evolution of civil society, fostering an environment conducive to the compatible cohabitation of culturally and socially diverse groups while at the same time encouraging social integration, with improvements in the quality of life for all segments of the population" (Polèse & Stren, 2000, p. 15).

Researchers focusing on Polish towns and large-scale centrally planned estates touch on social conditions and threats, and the survival potential for such estates, and highlight the relevance of the physical space and social changes occurring in the specific estates (Table 2).

Table 2. Selected research on large-scale centrally planned estates in Poland

Town level	Estate level
Warszawa (Musterd & van Kempen, 2005; Fuhrmann, 2010; Kozłowski, 2010) Białystok (Baum, 2018) Gdańsk (Rzyski & Mędrzycka, 2010) Kraków and Jędrzejów (Radziejowska & Sobotka, 2021) Łódź (Szafrańska 2009; 2014; Marcińczak & Sagan, 2011; Galuszka, 2022) Poznań, Kraków, Tarnów, Dzierżoniów, and Żyrardów (Gorczyca, 2016)	Ursynów and Wrzeciono in Warsaw (Węcławowicz, 2003) Stegny and Sadyba in Warsaw (Fuhrmann, 2010) Olechów-Janów in Łódź (Galuszka, 2022) Kaliny and Przyjaźń in Szczecin (Wojtkun, 2011) Tysiąclecia in Katowice (Komar, 2012) Mickiewicza in Lublin (Rodzoś & Flaga, 2010) Nowa Huta in Kraków (Stenning, 2005; Gądecki, 2012) Gaj and Sobieskiego in Wrocław (Borowik, 2003)

Source: own work.

THE CONSTRUCTION OF PREFABRICATED HOUSING ESTATES IN WARSAW IN THE 1970s AND 80s

The large-scale delivery of prefabrication housing was only possible due to the variety of methods and designs (Chyliński, 1965; Rębowska, 2006; Wojtkun 2008; Słodczyk 2010, 2012). Quintessential to that was the Prototype Estate established in 1959 in the Służew area of Warsaw, which by 1965 included over 20 examples of designs that were used later to master the full new estates and wider new neighbourhoods (Chyliński, 1965). PBU, WUF-T, OW-T, the Szczecin system, W-70, Wk-70, and H-frame were the most popular systems (Chomątowska, 2021).

In 1965–1970, the central plans determined the housing standards and designs, and prefabrication became a widespread solution for rapid housing production. By the late 1970s, there were 180 prefabrication plants – 'house factories' (Kiciński, 2004). The 1980s – despite the political and economic tensions – still saw mass implementation of several projects (Trybuś, 2018). For Warsaw, this meant large-scale greenfield developments in the farming outskirts and no barriers to access large land parcels that were easily nationalised under central planning conditions (Fig. 2). However, due to economic and land management deregulation, hyper-inflation and political changes, by the late 1980s, large-scale housing prefabrication was practically over. This opened the construction scene for private developers.

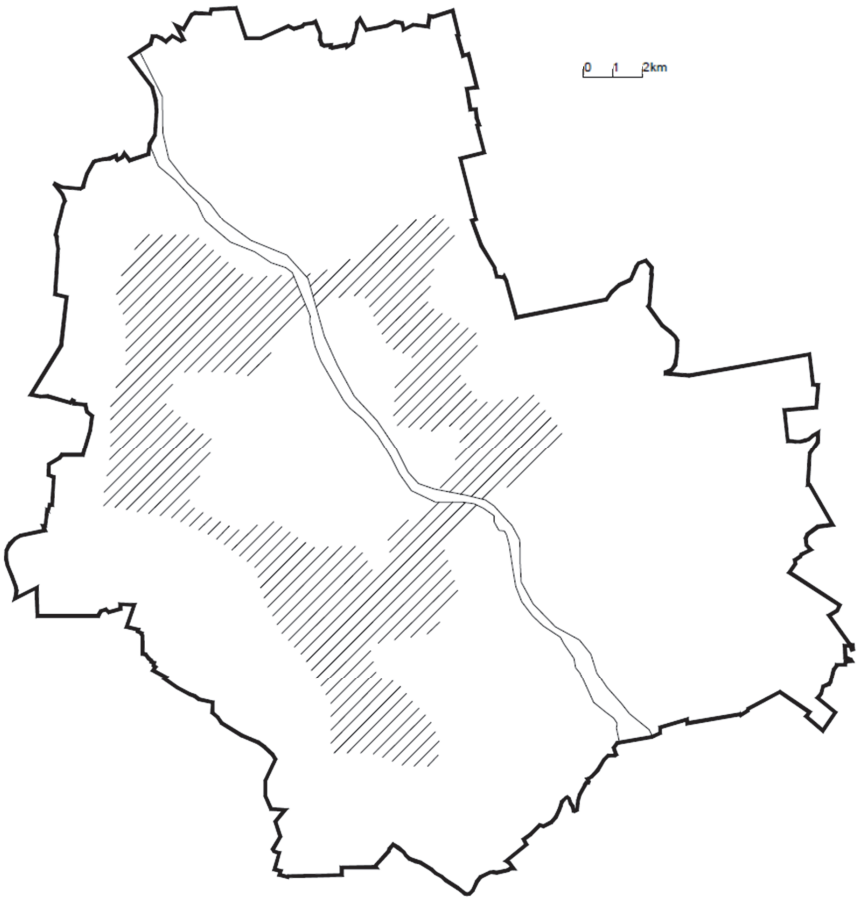


Fig. 2. Warsaw's areas developed with 1970s and 80s housing estates (marked by a hatched pattern)

Source: own work.

In Poland, there are around 60,000 prefabricated residential buildings inhabited by approximately 12 million people (Ministerstwo Funduszy i Polityki Regionalnej, 2019a, 2019b). Prefabricated apartments make up about 20% of the total housing stock (Heritage Real Estate [HRE] & United Nations Global Compact [UNGC], 2018). Most prefabricated estates are located in cities and larger towns. In Warsaw, they constitute some 22% of the whole stock, which is used by some 600,000 inhabitants (Wojtczuk, 2021). Many of Warsaw's projects are special for their scale, distinctive urban design, architectural form, and layout of individual multifamily buildings.

Prefabricated housing estates are typically viewed through the lens of their distinctive architectural form (Turkington, van Kempen & Wassenberg, 2004). However, there is more to it. Such estates are based on completely different urban planning assumptions than those applied to traditional urban patterns. From the 1960s, Polish architects and urban planners were able to fully implement the Athens Charter manifesto (CIAM, 1933). In the 1970s, as a result of the increased production of prefabricated housing, the shaping of large-scale free urban layouts on greenfield sites became virtually the only way of planning. In 1980, prefabricated units constituted 79% of all new completions (Radziszewska-Zielina & Gleń, 2014). New urban layouts were mainly designed with the aim of providing the minimum yet fully functional residential accommodation (Kiciński, 2004). The urban plans of residential estates demonstrate individual features of a compositional nature. The often-invisible relationships between the buildings were shaped by specific urban plan geometrical arrangements (Fig. 3) and ample provision of interconnected green spaces (Fig. 4). In many cases, these compositions, instead of being dictated by functional considerations, were an artistic manifestation of the concept's authors (Trybuś, 2018). Thus, the 1970s and 80s prefabricated projects are distinct from four perspectives: (1) urban design; (2) green space; (3) social infrastructure; and (4) architectural form and layout.

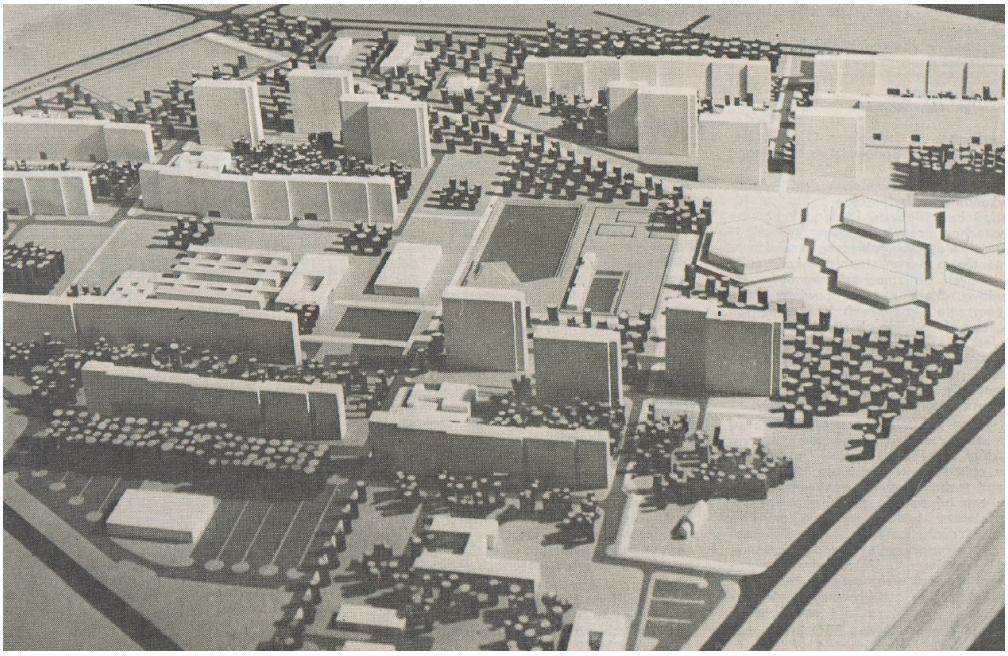


Fig. 3. Chomiczówka

Source: Dyteniecki and Steller (1973).

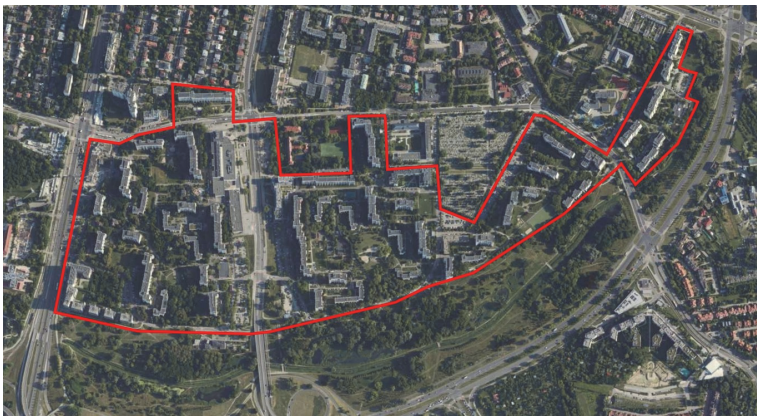


Fig. 4. Służew nad Dolinką

Source: Orthophotomap (Główny Urząd Geodezji i Kartografii [GUGiK], 2023).

Urban design

Warsaw's prefabricated housing estates were of a large scale, in excess of 100 ha. Thus, such estates, including Targówek Mieszkaniowy, Gocław, Jelonki, Marymont Ruda and Ursynów, are distinguished by carefully designed urban layouts and well-thought-out functional solutions. Ursynów Północny, designed by a team led by Marek Budzyński, is quintessential of it. Ursynów Północny was the largest single-phase residential complex in Poland (~40,000 residents), showcasing the level and capabilities of construction during that period (Ilmurzyńska, 2018). Here, apart from careful handling of the scale of the buildings and their form, the road layout and greenery provide critical compositional elements. Moreover, in some parts of Ursynów, the designers managed to combine the scale and atmosphere of a small town with lavish greenery for every resident (Fig. 5). Hence, the irony of history is that these large-scale estates delivered some of the pre-WWII ambitions for a concept known as Functional Warsaw (Różański, 1930; Kohlrausch, 2014).



Fig. 5. Ursynów Północny. After close to five decades, the estate is dominated by the diverse greenery

Source: landscape survey (own photo).

Green space

The greatest strength of urban design in the 1970s and 80s was the abundance of biologically active areas that were fully open to the public. This was possible due to the use of vast, formerly predominantly agricultural greenfield land (Mioduszewska, 2009). The greenery somewhat accidentally delivered a large chunk of the 'airing corridors' planned for Warsaw in 1928 (Różański, 1930). Green areas were developed with various types of greenery, ranging from simple plantings of birches, poplars and conifers to complex, carefully designed parks such as in the Szwoleżerów housing estate. This estate was designed by the leading architect of the time – Halina Skibniewska – with greenery and ornamental features designed by a renowned landscape architect, Alina Scholz (Fig. 6). While the Szwoleżerów estate has been designed on a smaller scale, it has been considered as a reference for other larger developments where such a high aesthetic level could not be fully achieved. Irrespective of the degree to which the green areas were developed, their capacity to absorb rainwater and moderate the urban heat island effect, as well as the availability of suitable space for especially tall tree species, proved to be a major benefit for the current residents. This is of particular importance, as such features stand in contrast to the very intensive developments carried out after 1989, in which access to greenery is significantly restricted (Fig. 7).



Fig. 6. Szwoleżerów. The park designed by Alina Scholtz plays a key role in the urban composition

Source: landscape survey (own photo).



Fig. 7. Kabaty – the southern part of the Ursynów District, developed in the 1990s, refers to classic frontage urbanism with limited public green space

Source: landscape survey (own photo).

Social infrastructure

The major problem with the urban planning assumptions of the 1970s and 80s in Poland was that they were hardly ever fully completed (Trybuś, 2018). Implementation usually started with residential buildings, which improved the housing production statistics and fulfilled the pent-up demand. This was then followed by associated services such as schools, shops and social venues such as clubs and cultural centres. In some cases, the expansion of some social infrastructure buildings was abandoned due to the lack of funds, or they were added after several years (Kiciński, 2004; Trybuś, 2018). In Ursynów Północny, the cinema and cultural centre was opened to the public in 1984, close to a decade after the completion of the first residential building (Dom Sztuki, 2023; Fig. 8). Similar situations also applied to road infrastructure and landscaping. The first Warsaw underground line is quintessential of that, with construction spreading between the early 1980s and mid-1990s and the construction sites cutting through the prefabricated Służew nad Dolinką and the whole Ursynów District, with many areas along the underground line only developed after its completion in the mid-1990s. Overall, the feeling of temporality, in many cases, was to accompany the new residents, often until the end of the 1980s. The lack of basic services and traditional urban forms such as streets with frontages and squares further hindered the formation of social ties (Mioduszewska, 2009).



Fig. 8. Dom Sztuki in Ursynów Północny

Source: GoogleMaps – Street view (Google, n.d.).

Architectural form and layout

The 1970s and 80s prefabricated architectural form, in individual cases, depended on the type of production of the nearest prefabrication factory. The role of architects during this period was to glue together ready-made large-scale elements. Hence, the major drawback of prefabricated housing architecture in Poland was its monotony (Kiciński, 2004; Mioduszewska, 2009; Trybuś, 2018). The façades of buildings usually looked very similar throughout. Exceptional solutions were rare. However, interesting solutions such as large balconies and generous green areas can also be found, e.g. in Służew nad Dolinką, designed by Janusz Nowak, Jerzy Kuźmienko and Piotr Sembrat and constructed using the then-newest H-frame technology (Chomątowska, 2021; Fig. 9).



Fig. 9. Służew nad Dolinką. Each apartment includes a square balcony of 4 m^2. Now, these balconies frequently serve as winter gardens. Ample green areas allow for the generous provision of playgrounds, while the greenery provides shade and noise reduction

Source: landscape survey (own photo).

Most often, prefabricated concrete façade elements with wooden windows were used, while the staircases were finished with a terrazzo floor, and the interior walls were plastered and painted with washable paint. With a construction scale of more than 200,000 dwellings per year, building repetitiveness had a major impact on the urban landscape. Thus, Warsaw, in the areas of new housing estates, was losing its unique character. Moreover, given the limited variation of prefabricated elements, there was little scope for creative innovation in housing. Frequently, apartments included small rooms, windowless kitchens or dysfunctional bathrooms (Basista, 2001; Szafrańska, 2017). Despite these deficiencies, the housing layouts were distinguished by consistency and economy of space with an ergonomic functional layout. The size of dwellings was determined by government norms. Following the 1959 residential development norm, according to which the size of dwellings in Poland was the smallest in Europe, the 1974 residential development norm was again updated, bringing dwelling size closer to the European average. For one-room dwellings for one person the norm was 25–28 m^2, two-room apartments for two people was 30–35 m^2, apartments for three people was 44–48 m^2, apartments for a four-person family was 56–61 m^2, apartments for a five-person family was 65–70 m^2, and apartments for a six-person family was 75–85 m^2 (Korzeniewski, 1980). With such a small footprint, ensuring an adequate number of rooms and windows has been a difficult design task. However, designing according to such demanding guidelines resulted in efficient layouts. Although the apartments were larger in Western Europe, the carefully designed apartments were delivered as fully finished. This stands in contrast with the post-1989 private developer-built apartments completed to the so-called developer standard, i.e. with kitchen, toilet, bathroom, and floor finishes to be installed by the purchaser. Currently, multifamily housing is not burdened by any norms, except for the minimum area of the apartment of 25 m^2 (Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r.). This significantly reduces the quality of the living space. It is also worth noting that in the multifamily buildings of the 1970s and 80s, apartments were accompanied by pram/bike rooms, clothes dryer rooms and individual storage units in the basements. In some cases, art studios were provided on the top floors.

As presented above, the 1970s and 80s residential prefabricated housing estates, while delivered during austerity times, were designed to serve society in many ways beyond just the pure-housing function, with many features that are frequently more appreciated now than when they were designed and delivered (Table 3).

Table 3. Key social sustainability features of Warsaw's residential prefabricated housing estates from the 1970s and 80s

Category	1970s and 80s
Green space	Large and frequently contiguous greenery, fully open green spaces, a large reserve of land for future green development, and green areas generating positive externalities for other parts of the city
Architectural form and layout	Convenient and compact apartments with common amenities, the highest availability of housing in Poland's history, and social diversity (economic and educational)
Social infrastructure	Availability of social infrastructure such as nurseries, kindergartens, schools and community centres, convenient transportation links with other parts of the city

Source: own work.

Since the 1990s, when the mass prefabrication was practically abandoned, many architects and researchers saw a bleak future for these estates in Warsaw (Kiciński, 2004; Trybuś, 2018). Trybuś (2018) suggested that one would have to decide what to do by choosing between demolishing; following what is done in Germany or the United States by large-scale top-down transformation (attempts of this have not been successful); bottom-up, smaller-scale activities; or simply waiting till the buildings fall apart. To that, Kiciński (2004) focused more on the need to keep upgrading. Many researchers also feared or predicted social decay (Jałowiecki, 1995; Czepczyński, 1999; Gaczek & Rykiel, 1999; Rykiel, 1999; Kiciński, 2004) to the extent that Rembarz (2010) coined the term 'large housing estate syndrome' to describe the social and physical degradation.

THE CURRENT STATE OF PREFABRICATED HOUSING ESTATES IN WARSAW

This section provides an overview of the current situation in Warsaw and highlights the major challenges for 1970s and 80s prefabricated housing estates, with particular focus on the implications of social and economic changes since the early 1990s, the changing perceptions of these types of developments, threats to green spaces, and differences between the 1970s and 80s housing estates and post-1989 estates.

Social and economic changes following the Iron Curtain

After 1989, Warsaw's inhabitants regarded prefabricated housing estates as a relic of the communist system. Moving to new buildings constructed by private developers or to single-family houses built mostly in the suburbs was a proof of social advancement (Szafrańska, 2016). The Ursynów District was an exceptionally good example, as it was largely transformed by urban planning. The main road artery, Aleja KEN, was built up with western-style commercial frontages. The main impetus for the expansion and development of the wider Ursynów District was the opening of the first underground line in 1995 (Żylski, 2019). While the 1980s Ursynów Północny is a clear example of prefabricated housing, Kabaty – the southern part of Ursynów – completed in the 1990s, is a compact and more densely developed area (Żylski, 2019), but at least with respect to the original 1980s road layout (Fig. 7).

In the 2010s, when housing prices skyrocketed, the estates of the 1970s and 80s regained their popularity (Szafrańska, 2016). The convenient location, lower price and transport links to the city centre were of major benefit in the rapidly growing housing market. The increasing residents' appreciation for green spaces and openness of estates meant that the maintenance of areas around the buildings improved, and they were landscaped to new standards (Musterd & van Kempen, 2005). However, with the growing economic diversification of the society, many new housing estates attempted to fence off (Wojtkun, 2007), often spiralling into spatial chaos. Despite new private developments, large-scale prefabricated housing projects managed to avoid being fenced off and remain open to all. Increasingly well-maintained green areas with tall greenery, which in the 21st century have reached their target height, further enhance public spaces. Typically,

cooperatives managing these housing estates implemented well-planned changes to ensure the long-term liveability of such places. As noted by Szafrańska (2014), many authors refer to that as 'modernisation', 'restructuring', 're-urbanisation', 'regeneration', 'rehabilitation' or just 'humanisation' (Chmielewski & Mirecka, 2001; Borowik, 2003, 2007; Węcławowicz, 2003; Rębowska et al., 2006; Gruszecka, Gzell & Rembarz, 2009; Ostańska, 2009; Kozłowski, 2010; Rembarz, 2010).

Prefabricated housing projects, when developed, were not expected to last forever but for just some 50 years (Szulc et al., 2018). By the early 21st century, the stock was deteriorating but still in reasonable shape, with major defects including scratches, leaks, damage to balconies, loggias, attics, the textured layer of wall panels, and utility installations (Szulc et al., 2018). Given these and observations of technical obsolescence of multifamily buildings in Western Europe (Musterd & van Kempen, 2005), in the 1990s, owners of large-scale prefabricated estates (predominantly housing cooperatives) started a debate on the technical condition of their stock. This frequently resulted in setting up long-term refurbishment programmes to increase the lifespan of the developments by thermal insulation, asbestos removal, window replacement, and upgrades to heating, electrical and ventilation systems (Szulc & Piekarczuk, 2022). This eventually resulted in government interventions such as the current Act on Supporting Thermal Insulation and Refurbishment (Ustawa z dnia 23 stycznia 2020 r.). The upgrade processes were accompanied by several technical surveys, which have proven that with rather limited improvements, the buildings are generally structurally sound. Thus, their lifespan has been redefined. According to a report on the technical condition of prefabricated buildings prepared in 2018 by the Polish Institute of Building Technology (ITB), the service life of these buildings can be extended to some 120 years, making them usable until the 2090s–2100s (Szulc et al., 2018). Thus, the buildings are continuously modernised, with a focus on thermal insulation to minimise residents' costs of living. However, new façades clad in polystyrene foam pose a major aesthetic problem. The original form of façades is transformed and often painted in colours that are not in harmony with the surroundings, resulting in an odd-coloured chaos which Filip Springer labelled as *pastelosis* (Springer, 2013). Fortunately, the growing awareness of Warsaw's residents means that after a wave in the late 1990s and early 21st century, this phenomenon is slowly fading. Moreover, the current interest in modernist architecture means that contemporary modernisations are still incorporating the aesthetic assumptions of architects from the 1970s and 80s.

Social perception of prefabricated housing estates in Warsaw

The functional and aesthetic assumptions on both sides of the Iron Curtain before the complete collapse of the Warsaw Pact in 1991 were not fundamentally different, as they were mainly defined before the division between the two political zones. As Moravčíková (2018) notes, all manifestations of the Modern Movement discovered or rediscovered behind the former Iron Curtain confirm the position of the Modern Movement as a solid and very European phenomenon. Contrary to earlier opinions about the drastic differences between the eastern and western parts of the Iron Curtain, the prevailing view today is the one in which universal elements emerge regardless of the political system (Dragostinova & Fidelis, 2018). Still, it is worth looking at the differences to understand the essence of the functioning of prefabricated housing in Warsaw. The nature of the space of these housing estates can appear to be almost the same regardless of geographical location, which can also lead to erroneous conclusions in assessing this space. There are two key issues here: social – determining the functioning of the estate and the neighbourhood, and environmental – access to green spaces and their impact on wellbeing.

The reception of modernist large-scale prefabricated housing estates on the western side of the Iron Curtain is often linked to class segregation (Hess, Tammaru & van Ham, 2018). In a post-communist, virtually classless society, the prefabricated estates were inhabited by representatives of different professions and incomes. In Warsaw's large-scale prefabricated housing estates, one can still find lawyers, workers, or doctors harmoniously living in the same building (Szafrańska, 2014). Despite an outflow of the wealthiest inhabitants,

this social diversity is still largely maintained, and these estates remain as safe as the gated communities, including even the significantly less affluent ones such as Wrzeciono in the Bielany District (Musterd & van Kempen, 2005; Szafrańska, 2017). Critics of Pruitt Igoe and of other similar projects in Western Europe blamed modernist architecture for the projects' failure (Montgomery, 1985). A new look at the estates' demise, however, includes a critical approach to the social aspect of the projects that resisted racial segregation, combined with the problem of unemployment. Ghettos similar to Pruitt-Igoe still exist today, even in more affluent areas, e.g. in the UK (Turkington, van Kempen & Wassenberg, 2004). The suburbs north of Paris are fraught with the same issues relating primarily to social policy (Blanc & Stebe, 2004). Given Warsaw's experience, blaming modernist prefabricated architecture for failures in social terms, therefore, seems to be debatable.

While the prefabricated housing estates in Warsaw can hardly be described as perfect, decades later, they are functioning as required. As summarised by Szafrańska (2016), across Poland, despite some symptoms of social separation and outflow of the wealthiest inhabitants, the social degradation predicted in the 1990s has not occurred. In Warsaw, this is clearly visible, e.g. in the Ursynów District (Węcławowicz, 2003; Musterd & van Kempen, 2005). Research done by Realizacja sp. z o.o. (2017) regarding the identity of Warsaw's residents further confirmed that the prefabricated housing is not stigmatised but part of the city's identity. More recently, Omyła-Rudzka (2022), reporting on the Public Opinion Research Centre (CBOS) national housing preference survey, observed that for the residents of major cities, the social infrastructure – such as schools, nurseries, shops, services and safety – was top-ranked. These were followed by access to green spaces, apartment size, public transport, transportation time to work or educational facilities and access to parking spaces. In the case of Warsaw, all these criteria cannot be easily met by newer developments, which explains the success of the 1970s and 80s estates.

The role of public green space in large-scale prefabricated housing estates in Warsaw

Another important issue that differentiates the prefabricated housing developments in Warsaw and other cities on the eastern side of the Iron Curtain relates to the easy access to land in the 1970s and 80s. In the Eastern bloc, the communist authorities, frequently following expropriation (effectively through forced land nationalisation), were able to provide sites for large-scale developments, allowing for vast amounts of green spaces for active recreation, parks and rainwater management. Contrary to the current regulations, the 1974 residential development norm prescribed the minimum green and social open spaces of 8 m^2 per person (Korzeniewski, 1980), providing what would now be seen as ample open space (Baum, 2018). Also, the incomparably slower development of car transportation in central and eastern European countries contributed to the abandonment of the construction of underground car parks, which made it possible to preserve even more biologically active areas. However, the increasing car ownership, financial constraints of the cooperatives managing the estates and increasing land values frequently lead to densification (Żylski, 2019), which is a major threat to the existing green areas.

Prefabricated housing estates vis-à-vis new private developer housing estates in Warsaw

After 1989, the government and cooperative housing production slowed down dramatically and started to be gradually replaced by multifamily estates provided by private developers. In these new projects, urban and architectural form changed towards postmodernism, which turned more towards traditional solutions, breaking away from 40 years of communism. These privately financed investments have been built on much smaller plots with severely restricted access to green space. The private profit-seeking housing developers maximised the density to its physical limits (Gyurkovich & Sotoca, 2019), resulting in green space set at the minimum specified, which was mostly far lower than the past norm.

The rapid growth of car ownership meant that most of the land outside the buildings needed to be dedicated to parking. Further, the increasing availability of housing loans led to an unprecedented real estate boom

in the first years of the 21st century, with forms and aesthetics determined by developers' profit maximisation with little attention to delivering social value to the estates. Paradoxically, the financial crisis of 2008, limiting access to mortgage funding, pushed the developers towards more attractive solutions for functionality over size and reversing back to simplified forms (Trębacz & Mazur, 2020). At the same time, several of the new housing projects were delivered as part of gated communities, of which, in Poland, most are located in Warsaw. Even very prestigious projects, such as APA Kuryłowicz & Associates' Marina Mokotów of 21 ha, turned out to be a closed fortress rather than a well-integrated estate. The fencing off of housing estates was not an architectural idea, but a marketing requirement, driven largely by the increase in crime in the 1990s and the perception of the problem persisting. This proved to be overconservative, as now Warsaw is the eighth safest capital city in Europe (Numbeo, 2025).

Residential development since the 1990s has been closely linked to the number of parking spaces, which has had a significant impact on the building form and on the layout of the apartments themselves, resulting in, for example, replacing basements and other common spaces with underground parking. Apartments built in the large-panel system were designed without this impediment, which facilitated the creation of functional yet small apartments. On the other hand, the lack of previously planned parking spaces has resulted in the use of public land for car parks, which has significantly reduced the original attractiveness of green spaces (Fig. 10). This change has often resulted from grassroots action by the residents themselves (Nóżka & Smagacz-Poziemska, 2018). In the longer term, reclaiming these areas for public use and a well-maintained urban green space is possible. However, that requires further improvements to the public transport system.



Fig. 10. Gocław. Public space that used to be a safe and green place for residents is being turned into a car park

Source: landscape survey (own photo).

In addition to the differences related to access to land for construction, the apartments' layout evolved. Currently, typically the living room and kitchen are combined in one room, which leaves more space for bedrooms and other areas. Unfortunately, the economics of construction also determined the increased width of the buildings, which means that access to natural light in the central parts of the apartments is more limited than in the 1970s and 80s apartments. While the on-site reinforced concrete technology has contributed to the freedom to design functional layouts, frequently these are less logical than in the prefabricated pre-1989 apartments. In favour of the new apartments is undoubtedly their standard of construction and technological solutions, far superior to the prefabrication designed in a communist country struggling with the economic crisis.

CONCLUSION

Despite the many flaws that characterised Warsaw's prefabricated housing estates, it should be noted that they have stood the test of time. Today, they are a point of reference for contemporary buildings. The greatest advantage of these estates is the fairly well-designed layout of the estates and apartments, which also function well in the 21st century. On an urban scale, the assessment seems ambivalent. On the one hand, the rapid construction of estates devastated the urban character of Warsaw. On the other hand, it provided green spaces that would not have been possible to achieve in free market conditions. In this context, prefabricated housing estates can be considered sustainable, with newer developments relying on the 1970s and 80s provision of green spaces.

Should these estates be treated as a model for development? Surely not. The number of defects that are an inseparable part of them excludes such an understanding – prefabricated buildings are difficult to adapt to new functions, which limits their future life to residential uses. However, the way in which the urban living environment is shaped in the current conditions seems irrational. Hence, the heritage of the 1970s and 80s estate should be relied on because, in the context of the existing urban public infrastructure, they moderate the impact of the development densification.

Prefabricated housing estates from the 1970s and 80s – despite not being sustainable spaces – can influence the sustainable development of the entire city in a broader urban context. Their location, forming a ring around the city centre, provides a reserve of green areas. It seems that these housing estates should be given similar protection to that applied to historical monuments. The best example of this is the Szwoleżerów housing estate, which has been entered in the heritage register (Order No. 1336/2016 of the Mayor of Warsaw). This type of protection may prevent the densification of buildings within the estates, which will ensure that the most valuable element of this space, i.e. greenery, remains in the overall structure of the city.

It is expected that the observations made in this research will help policymakers, planners, architects and developers in promoting suitable improvements to similar prefabricated housing estates in other parts of Poland and across Central and Eastern Europe and elsewhere, where city housing is dominated by similar types of developments.

Authors' contributions

Conceptualisation: G.W.R. and R.M.; methodology: G.W.R. and R.M.; validation: G.W.R. and R.M.; formal analysis: G.W.R. and R.M.; investigation: G.W.R. and R.M.; resources: G.W.R. and R.M.; writing – original draft preparation: G.W.R. and R.M.; writing – review and editing: G.W.R. and R.M.; visualisation: G.W.R. and R.M.; supervision: G.W.R. and R.M.; project administration: G.W.R. and R.M.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Adamec, J., Janoušková, S. & Hák, T. (2021). How to Measure Sustainable Housing: A Proposal for an Indicator-Based Assessment Tool. *Sustainability*, *13* (3), 1152. https://doi.org/10.3390/su13031152

Basista, A. (2001). *Betonowe dziedzictwo*. Warszawa: Wydawnictwo Naukowe PWN.

Baum, M. (2018). The 1974 Urban Planning Norms in the Shaping of Green Areas on the Example of Białystok. *Architektura Krajobrazu*, *3*, 38–49. https://doi.org/10.30825/5.ak.158.2018.60.3

Blanc, M. & Stebe, J-M. (2004). France – From dreams to dillusion. In R. Turkington, van R. Kempen & F. Wassenberg (Eds), *High-rise housing in Europe: current trends and future prospects*. Delf: DUP Science.

Borowik, I. (2003). *Blokowiska: miejski habitat w oglądzie socjologicznym: studium jakości wrocławskich środowisk mieszkaniowych.* Wrocław: Arboretum.

Borowik, I. (2007). Kierunki przemian współczesnego miasta – suburbanizacja oraz humanizacja blokowisk. In I. Borowik & K. Sztalt (Eds), *Współczesna socjologia miasta. Wielość oglądów i kierunków badawczych dyscypliny* (pp. 97–104). Wrocław: Wydawnictwo Uniwersytetu Wrocławskiego.

Brandon, P. S. & Lombardi, P. (2011). *Evaluating Sustainable Development in the Built Environment* (2nd ed.). Chichester: John Wiley.

Burczynski, D. (2017, November 6). *Czas na czterdziestolatka. Osiedle Ruda odżyje*. Retrieved from: https://tustolica.pl/czas-na-czterdziestolatka-osiedle-ruda-odzyje_76251 [accessed: 19.08.2025].

Chmielewski, J. M. & Mirecka, M. (2001). *Modernizacja osiedli mieszkaniowych*. Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej.

Choguill, C. L. (1994). Sustainable housing programme in a world of adjustment. *Habitat International*, *18* (2), 1–11. https://doi.org/10.1016/0197-3975(94)90047-7

Chomątowska, B. (2021). *Betonia. Dom dla każdego* (2nd ed.). Wołowiec: Wydawnictwo Czarne.

Chyliński, B. (1965). Osiedle Prototypów na Służewcu w Warszawie. *Architektura*, *8–9*, 213–214.

Congrès international d'architecture modern [CIAM]. (1933). *La Charte d'Athenes*. Retrieved from: https://designmanifestos.org/congres-internationaux-darchitecture-moderne-ciam-the-athens-charter/ [accessed: 05.07.2025].

Crowley, D. & Reid, S. E. (Eds) (2002). *Socialist Spaces: Sites of Everyday Life in the Eastern Bloc*k. Bloomsbury Publishing Plc. https://doi.org/10.5040/9781350057692

Czepczyński M. (1999). Rozwój i upadek koncepcji osiedli blokowych. *Biuletyn PAN – Komitet Przestrzennego Zagospodarowania Kraju*, *190*, 49–67.

Dempsey, N., Bramley, G., Power, S. & Brown, C. (2011). The Social Dimension of Sustainable Development: Defining Urban Social Sustainability. *Sustainable Development*, *19* (5), 289–300. https://doi.org/10.1002/sd.417

Ding, G. K. C. (2008). Sustainable construction – The role of environmental assessment tools. *Journal of Environmental Management*, *86* (3), 451–464. https://doi.org/10.1016/j.jenvman.2006.12.025

Dixon, T. (2019). Measuring the Social Sustainability of New Housing Development: A Critical Review of Assessment Methods. *Journal of Sustainable Real Estate*, *11* (1), 16–39. https://doi.org/10.22300/1949-8276.11.1.16

Dixon, T. & Woodcraft, S. (2013). Creating Strong Communities: Measuring Social Sustainability in New Housing Development. *Town and Country Planning*, *82*, 473–480.

Dom Sztuki (2023). *Archiwum*. Retrieved from: https://tinyurl.com/yc7rup6h [accessed: 19.08.2025].

Dragostinova, T. & Fidelis, M. (2018). Introduction. *Slavic Review*, *77* (3), 577–587. https://www.jstor.org/stable/26565649

Dyteniecki, Z. & Steller, S. (1973). Osiedla Wawrzyszew-Chomiczówka w Warszawie. *Architektura*, *10*, 383–385. Retrieved from: https://mbc.cyfrowemazowsze.pl/dlibra/publication/84038/edition/85959?language=en [accessed: 05.07.2025].

European Environment Agency [EEA] (2024). *Addressing the environmental and climate footprint of buildings* (EEA Report 09/2024). Retrieved from: https://www.eea.europa.eu/en/analysis/publications/addressing-the-environmental-and-climate-footprint-of-buildings [accessed: 20.08.2025].

Emerson, J. (2000). *The Nature of Returns: The Nature of Returns: A Social Capital Markets Inquiry into Elements of Investment and The Blended Value Proposition*. Boston: Division of Research, Harvard Business School. Retrieved from: https://www.fi-compass.eu/sites/default/files/publications/the-nature-of-returns-a-social-capitla-market-inquiry-into-elements-of-investment-and-the-blended-value-proposition.pdf [accessed: 05.07.2025].

Fuhrmann, M. (2010). Residents' Relationship with the Territory and the Spatial Planning of Residential Housing Developments. *Miscellanea Geographica*, *14* (1), 265–272. https://doi.org/10.2478/mgrsd-2010-0025

Gaczek, W. & Rykiel, Z. (1999). Nowe lokalizacje mieszkaniowe w przestrzeni miasta (New residential location within the urban area. *Biuletyn PAN – Komitet Przestrzennego Zagospodarowania Kraju*, *190*, 29–47.

Gądecki, J. (2012). *Gentryfikacja starej części Nowej Huty*. Warszawa: Instytut Filozofii i Socjologii Polskiej Akademii Nauk.

Galuszka, J. (2022). Beyond the decay? Positive patterns in the development of a large housing estate: the case of Olechów-Janów district in Łódź, Poland. *Urban Research & Practice*, *15* (2), 169–193. https://doi.org/10.1080/17535069.2020.1782459

Gąsowska-Kramarz, A. (2019). Pruitt Igoe vs City of the Future. *Architecture, Civil Engineering, Environment*, *12* (4), 15–21. https://doi.org/10.21307/acee-2019-048

Główny Urząd Geodezji i Kartografii [GUGiK] (2023). Retrieved from: Geoportal.gov.pl [accessed: 19.08.2025].

Google (n.d.). *Google Map*. Retrieved from: https://maps.google.com [accessed: 19.08.2023].

Gorczyca, K. (2016). The Social Transformation of Large Housing Estates in Poland at the Turn of the 21st Century. *Sociologický Časopis / Czech Sociological Review*, *52* (6), 861–892. https://www.jstor.org/stable/44817688

Gruszecka, K., Gzell, S. & Rembarz, G. (2009). Osiedle: Reurbanizacja [Residential estate: Reurbanisation]. *Urbanistyka – Międzyuczelniane Zeszyty Naukowe*, *14.*

Gyurkovich, M. & Sotoca, A. (2019). Quality of Social Space in selected contemporary multifamily housing complexes in Poland's three biggest cities. *IOP Conference Series: Materials Science and Engineering*, *471* (9), 1–9. https://iopscience.iop.org/article/10.1088/1757-899X/471/9/092009

Hess, D. B., Tammaru, T. & Ham, M. van (2018). *Housing Estates in Europe: Poverty, Ethnic Segregation and Policy Challenges*. Springer.

Heritage Real Estate [HRE] & United Nations Global Compact [UNGC] (2018). *Ile mieszkań brakuje w Polsce?* Retrieved from: https://bank.pl/wp-content/uploads/2018/12/Heritage-Raport-04-12-justowany.pdf [accessed: 05.07.2025].

Hoorn, M. van der (2004). Consuming the "Platte" in East Berlin: the new popularity of former GDR architecture. *Home Cultures*, *1* (2), 89–126. Retrieved from: https://dvqlxo2m2q99q.cloudfront.net/000_clients/481243/file/4812432AaKlHLG.pdf [accessed: 05.07.2025].

International Finance Corporation [IFC] (2015). *Affordable Housing is Good, Socially Sustainable is Even Better*. Retrieved from: https://ifc-org.medium.com/a-new-tool-to-make-your-housing-project-more-inclusive-and-resilient-5e076a96c1cd [accessed: 05.07.2025].

Ilmurzyńska, K. (2018). Ewolucja przestrzenna Ursynowa Północnego [Spatial evolution of Northern Ursynów in Warsaw]. *Przestrzeń – Urbanistyka – Architektura*, *1*, 203–218. https://doi.org/10.4467/00000000PUA.18.015.8623

Jałowiecki, B. (1995). Miasto polskie – między utopią a rzeczywistością. In P. Starosta (Ed.), *Zbiorowości terytorialne i więzi społeczne* (pp. 36–43). Łódź: Wydawnictwo Uniwersytetu Łódzkiego.

Jencks, Ch. (1977). *The language of post-modern architecture*. London: Rizzoli.

Kalfaoglu Hatipoğlu, H. (2017). Understanding social sustainability in housing from the case study 'Wohnen mit uns' in Vienna and adaptibility to Turkey. *ICONARP International Journal of Architecture and Planning*, *5* (1), 87–109. https://doi.org/10.15320/ICONARP.2017.19

Kaźmierczak, M. (2021, July 22). *Rynkowy renesans mieszkań z wielkiej płyty. Drożeją szybciej od nowszych lokali i kamienic.* Retrieved from: https://www.bankier.pl/wiadomosc/Rynkowy-renesans-mieszkan-z-wielkiej-plyty-Drozeja-szybciej-od-nowszych-lokali-8157015.html [accessed: 05.07.2025].

Khor, S. C. S. & Abu Bakar, A. H. B. (2012). Incorporating sustainable management system into housing development practice in Malaysia. *International Journal of Sustainable Development*, *15* (3), 277–291. https://doi.org/10.1504/IJSD.2012.047754

Kiciński, A. (2004). Poland – A future for the 'blokowisko'? In R. Turkington, van R. Kempen, F. Wassenberg (Eds), *High-rise housing in Europe: current trends and future prospects* (pp. 187–202). Delf: DUP Science.

Kohlrausch, M. (2014). Warszawa Funkcjonalna: Radical Urbanism and the International Discourse on Planning in the Interwar Period. In J. C. Behrends & M. Kohlrausch (Eds), *Races to Modernity: Metropolitan Aspirations in Eastern Europe, 1890–1940* (pp. 205–232). Budapest: Central European University Press.

Komar, B. (2012). Analiza historyczna rozwoju osiedli mieszkaniowych na podstawie wybranych przykładów: Grünau w Lipsku i im. Tysiąclecia w Katowicach na tle wzorcowych koncepcji mieszkalnictwa XX wieku [Historical analysis of development of housing estates: Grünau in Leipzig and Millennium in Katowice in connection with the background of the 20th century standard concept of housing]. *Architecturae et Artibus*, *2*, 13–25. Retrieved from: http://aeawa.pb.edu.pl/wp-content/uploads/2018/08/2-Komar.pdf [accessed: 05.07.2025].

Korusiewicz, J. (2025). *Warszawskie Blokowiska*. Retrieved from: https://www.blokowiska.waw.pl/dane [accessed: 19.08.2025].

Korzeniewski, W. (1980). *Normatyw urbanistyczny i mieszkaniowy*. Warszawa: Centralny Ośrodek Informacji Budownictwa.

Kozłowski, S. (2010). Przeszkody i bariery na drodze humanizacji osiedli. In I. Jażdżewska (Ed.), *Osiedla blokowe w strukturze przestrzennej miast* (pp. 73–87). Łódź: Wydawnictwo Uniwersytetu Łódzkiego.

Krippendorff, K. (2019). *Content analysis* (4th ed.). SAGE Publications. https://doi.org/10.4135/9781071878781

Marcińczak, S. & Sagan, I. (2011). The Socio-spatial Restructuring of Łódź, Poland. *Urban Studies*, *48* (9), 1789–1809. https://doi.org/10.1177/0042098010379276

Ministerstwo Funduszy i Polityki Regionalnej (2019a, 10 September). *Z Funduszem Termomodernizacji i Remontów do "wielkiej płyty" i samorządów*. Retrieved from: https://www.gov.pl/web/fundusze-regiony/z-funduszem-termomodernizacji-i-remontow-do-wielkiej-plyty-i-samorzadow [accessed: 05.07.2025].

Ministerstwo Funduszy i Polityki Regionalnej (2019b, 30 January). *Wielka płyta jest bezpieczna.* Retrieved from: https://www.gov.pl/web/fundusze-regiony/wielka-plyta-jest-bezpieczna [accessed: 05.07.2025].

Mioduszewska, Z. (2009). Historia bloku mieszkalnego jako koncepcji antropologicznej [History of an apartment block as an anthropological concept]. *Kultura i Społeczeństwo*, *53* (2), 3–19. https://doi.org/10.35757/KiS.2009.53.2.1

Montgomery, R. (1985). Pruitt-Igoe: Policy Failure or Societal Symptom. In *The metropolitan Midwest: policy problems and prospects for change* (pp. 229–243). Chicago: Urbana.

Moravčíková, H. (2018). Is there something behind the Iron Curtain? Documentation and conservation of Modernism in former Eastern Europe. *Docomomo Journal*, *59*, 4–5. https://doi.org/10.52200/59.A.CRLKS56S

Musterd, S. & Kempen, R. van (2005). *Large housing estates in European Cities – Opinions of residents on recent developments*. Utrecht: Urban and Regional research centre Utrecht, Faculty of Geosciences, Utrecht University.

Nicholls, J. (2023). *Social Value 2023. The Future of Social Value in The United Kingdom*. Social Enterprise UK. Retrieved from: https://www.socialenterprise.org.uk/seuk-report/the-future-of-social-value-in-the-united-kingdom/ [accessed: 05.07.2025].

Nóżka, M. & Smagacz-Poziemska, M. (2018). Różnice i granice z perspektywy relacyjnej koncepcji kultury i teorii praktyk społecznych. Przypadek wielkomiejskiego osiedla [On borders and differentiations in housing settlements,through the prism of social practices]. *Kultura i Społeczeństwo*, *62* (3), 121–141. https://doi.org/10.35757/KiS.2018.62.3.7

Numbeo (2025). *Europe: Current Safety Index by City.* Retrieved from: https://www.numbeo.com/crime/region_rankings_current.jsp?displayColumn=1&region=150 [accessed: 05.07.2025].

Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Infrastruktury w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie. Dz.U. 2022 poz. 1225. Retrieved from: https://isap.sejm.gov.pl/isap.nsf/download.xsp/WDU20220001225/O/D20221225.pdf [accessed: 05.07.2025].

Omyła-Rudzka, M. (2022). Jak Polacy chcieliby mieszkać? *Komunikat z Badań CBOS*, *108*. Retrieved from: https://www.cbos.pl/SPISKOM.POL/2022/K_108_22.PDF [accessed: 05.07.2025].

Orchowska, A. & Klimowicz, J. (2023). Osiedle Gocław – aspekt przyrodniczy w środowisku mieszkaniowym [Gocław Estate – A natural aspect in the residential environment]. *Housing Environment*, *43*, 66–77. https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-745dcbdf-9e0e-40f4-8e2e-7db34a226bcf/c/SM2023_43_66_OrchowskaA.pdf [accessed: 19.08.2025].

Ostańska, A. (2009). Problemy rewitalizacji zespołów prefabrykowanej zabudowy mieszkaniowej na przykładzie osiedla im. S. Moniuszki w Lublinie [Problems of regeneration of prefabricated residential estate based on a case study of the im. S. Moniuszki estate in Lublin]. *Budownictwo i Architektura*, *4* (1), 85–104. https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BPL2-0015-0006/c/httpwibis_pollub_plfilesplikikonferencje46.pdf [accessed: 19.08.2025].

Polèse, R. & Stren, M. (2000). *The social sustainability of cities: diversity and the management of change.* Toronto: University of Toronto Press. https://doi.org/10.3138/9781442682399

Public Services (Social Value) Act 2012. Retrieved from: http://www.legislation.gov.uk/ukpga/2012/3/pdfs/ukpga_20120003_en.pdf [accessed: 05.07.2025].

Radziejowska, A. & Sobotka, A. (2021). Assessment of large-panel prefabricated buildings in the social aspect of sustainable construction. *Archives of Civil Engineering*, *67* (3), 93–108. https://doi.org/10.24425/ace.2021.138045

Radziszewska-Zielina, E. & Gleń, M. (2014). Studies of the Prefabricated Housing Construction Market in Poland. *Journal of Civil Engineering*, *9* (2), 13–26. https://doi.org/10.2478/sspjce-2014-0012

Raiden, A., Losemore, M., King, A. & Gorse, C. (2018). *Social value in construction*. Routledge. https://doi.org/10.1201/9781315100807

Realizacja sp. z.o.o. (2017, February 16). *Tożsamość Warszawy i jej mieszkańców*. Retrieved from: https://tinyurl.com/bdhp2wv5 [accessed: 05.07.2025].

Rembarz, G. (2010). Rola przestrzeni publicznej w odnowie i kształtowaniu miejskiego środowiska mieszkaniowego. In P. Lorens & J. Martyniuk-Pęczek (Eds), *Zarządzanie rozwojem przestrzennym miast* (pp. 138–156). Gdańsk: Urbanista.

Rębowska, A. (Ed.) (2006). *Strategia rehabilitacji blokowisk – osiedli miejskich wznoszonych metodami uprzemysłowionymi*. Warszawa: Instytut Rozwoju Miast.

Rodzoś, J. & Flaga, M. (2010). Nowa sytuacja społeczna starych osiedli mieszkaniowych na przykładzie osiedla im. A. Mickiewicza w Lublinie. In I. Jażdżewska (Ed.), *Osiedla blokowe w strukturze przestrzennej miast* (pp. 101–118). Łódź: Wydawnictwo Uniwersytetu Łódzkiego.

Różański, S. (1930). Plan ogólny zabudowania m.st. Warszawy. *Kronika Warszawy*, *12*(VI).

Rykiel, Z. (1999). Przemiany struktury społeczno-przestrzennej miasta polskiego a świadomość terytorialna jego mieszkańców [The transformation of the socio-spatial structure of the Polish city versus the territorial consciousness of its inhabitants]. *Prace Geograficzne*, *170*. Retrieved from: https://rcin.org.pl/igipz/Content/600/Wa51_3580_r1999-nr170_Prace-Geogr.pdf [accessed: 19.08.2025].

Rzyski, S. & Mędrzycka, K. (2010). Osiedla blokowe versus inne formy zabudowy mieszkaniowej w Gdańsku – percepcja i waloryzacja warunków zamieszkania. In I. Jażdżewska (Ed.), *Osiedla blokowe w strukturze przestrzennej miast* (pp. 251–259). Łódź: Wydawnictwo Uniwersytetu Łódzkiego.

Słodczyk, J. (2010). Geneza i rozwój osiedli blokowych. In I. Jażdżewska (Ed.), *Osiedla blokowe w strukturze przestrzennej miast* (pp. 11–25). Łódź: Wydawnictwo Uniwersytetu Łódzkiego.

Słodczyk, J. (2012). *Historia planowania i budowy miast*. Opole: Wydawnictwo Uniwersytetu Opolskiego. Retrieved from: https://janusz-slodczyk.eu/wp-content/uploads/2020/03/J.S%C5%82odczyk-Historia-planowania.pdf [accessed: 19.08.2025].

Soo Cheen, S. K. & Abu Bakar, A. H. (2012). Incorporating sustainable management system into housing development practice in Malaysia. *Journal of Sustainable Development*, *15* (3), 277–291. https://doi.org/10.1504/IJSD.2012.047754

Spółdzielnia Mieszkaniowa "SM Szwoleżerów" (2025). Homepage smszwolezerow.pl. Retrieved from: http://www.smszwolezerow.pl/ [accessed: 19.08.2025].

Spółdzielnia Mieszkaniowa „Służew nad Dolinką" (2025). Homepage smsnd.pl. Retrieved from: https://www.smsnd.pl/ [accessed: 19.08.2025].

Springer, F. (2013). *Wanna z kolumnadą. Reportaże o polskiej przestrzeni.* Warszawa: Czarne, Warsaw.

Starzyk, A., Cortiços, N. D., Duarte, C. C., & Łacek, P. (2025). Timber Architecture for Sustainable Futures: A Critical Review of Design and Research Challenges in the Era of Environmental and Social Transition. *Buildings*, *15* (15), 2774. https://doi.org/10.3390/buildings15152774

Stenning, A. (2005). Transformation of Life, Work and Community in Post-socialist Europe: A Westerner Studies Nowa Huta, Poland. *Geographia Polonica*, *78* (1), 9–22.

Szafrańska, E. (2009). Atrakcyjność mieszkaniowa blokowiska w opinii mieszkańców na przykładzie zespołu mieszkaniowego Retkinia-Północ w Łodzi. In I. Jażdżewska (Ed.), *Duże i średnie miasta polskie w okresie transformacji* (pp. 197–210). Łódź: Wydawnictwo Uniwersytetu Łódzkiego, Łódź.

Szafrańska, E. (2014). Transformations of large housing estates in post-socialist city: The case of Łódź, Poland. *Geographia Polonica*, *87* (1), 77–94.

Szafrańska, E. (2016). *Wielkie osiedla mieszkaniowe w mieście postsocjalistycznym: geneza, rozwój, przemiany, percepcja*. Łódź: Wydawnictwo Uniwersytetu Łódzkiego.

Szafrańska, E. (2017). Zmiany w strukturze społecznej i demograficznej wielkich osiedli mieszkaniowych w postsocjalistycznej Polsce i ich główne determinanty [The changes in social and demographic structure of large housing estates in post-socialist Poland and their main determinants]. *Acta Universitatis Lodziensis. Folia Geographica Socio-Oeconomica*, *30*, 7–26. https://doi.org/10.18778/1508-1117.30.01

Szulc, J., Geryło, R., Możaryn, T., Piekarczuk, A., Wójtowicz, M., Lamenta, A., Mazurek, A., Sieczkowski, J., Strąk, A., Warsicka, D., Wojnowski, D. & Zięba, W. (2018). *Budownictwo wielkopłytowe. Raport o stanie technicznym.* Warszawa: Instytut Techniki Budowlanej. Retrieved from: https://budowlaneabc.gov.pl/budownictwo-wielkoplytoweraport-o-stanie-technicznym [accessed: 05.07.2025].

Szulc, J. & Piekarczuk, A. (2022). Diagnostics and technical condition assessment of large-panel residential buildings in Poland. *Journal of Building Engineering*, *50* (1), 104144. https://doi.org/10.1016/j.jobe.2022.104144

Trębacz, P. & Mazur, R. (2020). Typologia zabudowy mieszkaniowej wielorodzinnej w Polsce w latach 2010–2019 [Typology of multi-family residential developments in Poland in 2010–2019]. *Housing Environment*, *30*, 37–46. https://doi.org/10.4467/25438700SM.20.004.12207

Trybuś, J. (2018). *Przewodnik po warszawskich blokowiskach*. Łódź: Księży Młyn.

Turkington, R., Kempen, R. van & Wassenberg, F. (2004). *High-rise housing in Europe: current trends and future prospects*. Delf: DUP Science.

United Nations Economic Commission for Europe [UNECE] (2015). *Geneva UN Charter on Sustainable Housing*. Retrieved from: https://unece.org/DAM/hlm/documents/Publications/EN_Geneva_UN_Charter_on_Sustainable_Housing.pdf [accessed: 05.07.2025].

Ustawa z dnia 23 stycznia 2020 r. o zmianie ustawy o wspieraniu termomodernizacji i remontów. Dz.U. 2020 poz. 412. Retrieved from: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20200000412 [accessed: 05.07.2025].

Vassileva-Karagyozova, S. & Wood, N. D. (2012). The Socialist Prefabs after Utopia: "Non-places" or "Something Like Happiness"? *East European Politics and Societies*, *26* (3), 447–453. https://doi.org/10.1177/0888325412441825

Węcławowicz, G. (2003). Restrukturyzacja wielkich osiedli mieszkaniowych w miastach europejskich. Opis projektu badawczego [Restructuring of European residential neighbourhoods. Description of a research project]. *Przegląd Geograficzny*, *75* (3), 469–477.

Wiesel, I., Davison, G., Milligan, V., Phibbs, P., Judd, B. & Zanardo, M. (2012). *Developing sustainable affordable housing: A project level analysis. Australian Housing and Urban Research Institute & UNSW-UWS Research Centre* (Final Report 183). Retrieved from: https://www.ahuri.edu.au/research/final-reports/183 [accessed: 05.07.2025].

Wojtczuk, M. (2021, July 11). *Mieszkania w blokach z wielkiej płyty w Warszawie błyskawicznie znikają z rynku. Ceny? Nawet 17 tys. zł za metr.* Retrieved from: https://tinyurl.com/227ujkzb [accessed: 05.07.2025].

Wojtkun, G. (2007). Zamknięte społeczności – wybór czy konieczność? [Closed communities – choice or necessity?]. *Architektura Mieszkaniowa*, *7* (5), 154–162.

Wojtkun, G. (2008). Wielorodzinne budownictwo mieszkaniowe w Polsce. W cieniu wielkiej płyty [Multifamily residential construction in Poland. In the shadow of the large plate]. *Przestrzeń i Forma*, *10*, 175–194.

Wojtkun, G. (2011). Osiedla Kaliny i Przyjaźń w Szczecinie: „uniwersalna" wielorodzinna zabudowa mieszkaniowa [Kalina i Przyjaźń residential estates in Szczecin: "universal" residential development]. *Przestrzeń i Forma*, *16*, 609–622. https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-article-BPS1-0047-0084

Woodcraft, S., Bacon, N., Caistor-Arendar, L. & Hackett, T. (2011). *Design for Social Sustainability: A Framework for Creating Thriving Communities*. London: The Young Foundation. Retrieved from: http://www.social-life.co/media/files/DESIGN_FOR_SOCIAL_SUSTAINABILITY_3.pdf [accessed: 05.07.2025].

Żylski, T. (2019, February 11). *Osiedla Warszawy*. Retrieved from: https://architektura.um.warszawa.pl/-/publikacja-osiedla-warszawy [accessed: 05.07.2025].

BARDZIEJ ZRÓWNOWAŻONE NIŻ SIĘ WYDAJE – ROZWÓJ ZRÓWNOWAŻONY WARSZAWSKICH OSIEDLI MIESZKANIOWYCH Z LAT 1970–1980

STRESZCZENIE

Po upadku komunizmu, w 1989 roku, blokowiska w Warszawie stały się niechcianym dziedzictwem poprzedniej epoki. Niejednokrotnie charakteryzowały się one niską jakością wykonania, brakami w otaczającej infrastrukturze oraz monotonią przestrzeni miejskiej. Jednak od drugiej dekady XXI wieku są one coraz bardziej doceniane. W przeciwieństwie do innych stolic europejskich duże osiedla z lat 70. i 80. nie stały się odizolowanymi, biednymi dzielnicami miasta, ale raczej integralną częścią Warszawy, zróżnicowaną pod względem społeczno-ekonomicznym. Niniejsze badanie analizuje to zjawisko, aby wyjaśnić, w jaki sposób przestrzenie, które 30 lat temu były skazane na porażkę, mogą wpływać na budowanie miasta zrównoważonego. Pomimo wad blokowiska charakteryzują się nieosiągalnymi obecnie cechami, takimi jak: metraż i rozkład mieszkań oraz obszerne przestrzenie publiczne. Sposób, w jaki te osiedla funkcjonują dzisiaj, zmusza nas do zastanowienia się nad źródłami pozytywnego odbioru społecznego i różnicami w stosunku do inwestycji mieszkaniowych realizowanych w obecnych warunkach wolnorynkowych.

Słowa kluczowe: budownictwo wielkopłytowe, budownictwo wielorodzinne, zrównoważony rozwój społeczny, Polska

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EXPLORING THE BENEFITS OF OPENBIM STANDARDS FOR ENHANCED INTEROPERABILITY AND EFFICIENCY IN ARCHITECTURE, ENGINEERING, AND CONSTRUCTION PROJECTS

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ABSTRACT

This article presents an analysis of the impact of openBIM standards on interoperability and efficiency in construction projects. The hypothesis put forward is that the coordinated use of openBIM standards and services, such as IFC, BCF, bSDD, IDS, IDM, and UCM, improves the quality of information and reduces the number of errors during interdisciplinary coordination. For this study, 'efficiency' is defined as a composite of: (1) data quality, (2) coordination efficiency, and (3) time/cost (person-hours and related costs). The methodology combines a literature review with a practical case study of a conceptual BIM model of a museum building. The results indicate that each standard plays a distinct role: IFC enables uniform model transfer, BCF facilitates issue tracking, bSDD provides standardised semantics, IDS allows automatic data verification, IDM clarifies the flow of information between process participants, and UCM enables capturing and reusing best practices. Together, these standards improve data exchange, enhance coordination, and reduce errors. Challenges include limited tool support and the need for user training. In conclusion, openBIM standards support collaboration and efficiency; there is also a need for further research on their practical implementation.

Keywords: architecture, design, openBIM, IFC, bSDD, IDS

INTRODUCTION

The architecture, engineering, and construction (AEC) industry is complex and requires a collaborative approach. Nevertheless, project data is often fragmented across heterogeneous systems and processes. In many cases, building information remains detached, unstructured, and inconsistently represented across platforms and industries, making it difficult to exchange it effectively (Jiang et al., 2019a, 2019b). The insufficient unification of data exchange standards and methods contributes to information loss, misinterpretation, or inefficient manual repetition of activities, resulting in increased costs, delays, or errors. In response, the concept of openBIM has emerged as a holistic approach to digital collaboration based on open standards and transparent data workflows. Studies show that openBIM improves multidisciplinary coordination, enhances interoperability between different software, and ensures data consistency, thereby increasing overall project efficiency (Jiang et al., 2019a, 2019b; Gourabpasi, Jalaei & Ghobadi, 2025).

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At the core of openBIM is the Industry Foundation Classes (IFC) standard ISO 16739 (International Organization for Standardization [ISO], 2024), which is an open data schema for describing construction models. By providing a common data language, IFC enables the shared use of models across different software and disciplines, including architecture, engineering, mechanical, electrical, and plumbing (MEP), and various construction phases (Gourabpasi et al., 2025). Complementing IFC are other buildingSMART standards. The buildingSMART Data Dictionary (bSDD) provides a structured, multilingual classification of buildings and properties, ensuring semantic consistency and data quality that can be shared across different projects (Oraskari, 2021). The Information Delivery Specification (IDS) enables the expression of data requirements in machine-readable format (XML), which supports automated model validation. The Information Delivery Manual (IDM) outlines process maps and data exchanges between stakeholders, supporting the structured development of information models (Kim, Kwon, You & Lim, 2010). In addition, the Use Case Management (UCM) system serves as a collaborative platform to capture and share real-world BIM use cases, thereby supporting the standardisation and reuse of best practices. Together, these standards create a robust openBIM framework that governs data exchange throughout the asset lifecycle. Furthermore, initiatives such as the ISO/TC 59 Digitalisation Use Case underscore the growing importance of standardised digital workflows in the construction industry, highlighting the role of international standards in facilitating interoperable data exchange (Borgos, 2022). This highlights the crucial role of evolving openBIM standards in enabling efficient digital collaboration and process integration.

Although the benefits of open standards in BIM are increasingly acknowledged, the current literature lacks a comprehensive evaluation of their combined impact that highlights the benefits. Some studies have demonstrated the practical applications of openBIM, such as streamlining energy analysis workflows with the use of IFC, which significantly reduces preparation time and increases model reliability (Gourabpasi et al., 2025). Despite growing interest in openBIM, the integration and use of standards such as IFC, IDS, bSDD, IDM, and UCM remain underexplored.

This article aims to explore the benefits of applying openBIM standards – specifically, IFC, IDS, bSDD, IDM, and UCM – for improving data interoperability and project efficiency in the AEC industry. It hypothesises that the coordinated implementation of these standards enhances information quality, as well as reducing coordination errors and the time needed for their resolution, contributing to higher performance in construction projects. The study will examine both the functional scope and adoption challenges of these standards, as well as their potential to improve interdisciplinary collaboration across the construction value chain.

MATERIAL AND METHODS

This study uses a multi-step methodology combining literature review, industry insight and a practical case study based on a BIM model. First, a narrative literature review was conducted to identify the documented benefits of openBIM standards, including IFC, bSDD, IDS, IDM, and UCM. Official materials from buildingSMART and academic papers were included.

A narrative review of technical papers, standards documentation and case studies was performed to extract the key advantages of each openBIM standard. Databases such as ScienceDirect and Google Scholar were utilised, with a focus on works published between 2020 and 2025 to ensure that the research aligns with the latest applications of openBIM. Resources from buildingSMART (technical specifications, guides and platform materials) were essential in identifying the role of open standards in improving data exchange, model reliability and multidisciplinary coordination (buildingSMART, n.d.-a; buildingSMART, n.d.-b; buildingSMART, n.d.-c; buildingSMART, n.d.-d; buildingSMART, n.d.-e).

These documents are essential for understanding the intended usage of openBIM standards. The above-mentioned documents have a practitioner-oriented character and can be perceived as promotional.

buildingSMART describes standards and recommended workflows, but its claimed benefits need confirmation from independent research and their usage in the case study.

Qualitative insights were also given from the author's practical, professional experience working in the construction industry as an employee of a general contractor. Although anonymised, this perspective provides a picture of the practical benefits and challenges observed in the implementation of openBIM standards in real-world conditions. These insights supplement the theoretical findings from the literature.

Moreover, the case study was presented to illustrate the potential, practical implementation, and mutual integration of a wide range of openBIM standards in a project managed using BIM. The BIM model concerned a conceptual museum building located on the Vistula riverbank in Warsaw. The project comprised two levels (one underground and a ground floor with mezzanines in the exhibition space), modelled at the level of detail (LOD) 300, which is sufficient for design coordination and information validation tasks. The architectural model was created in ArchiCAD, and the structural model in Revit. The combined model was exported in IFC 4 format and included both architectural and structural elements. Disciplines covered are architecture, structure, and mechanical systems. This scope provides a representative scale for testing the practical integration of IFC, IDS, bSDD, BCF and related workflows.

Literature review – openBIM standards overview

OpenBIM emerged from IAI/buildingSMART initiatives in the mid-1990s and has since evolved into several vendor-neutral standards and tools enabling data exchange (Steinmann, 2024). Jiang et al. (2019a, 2019b) provided a broad review up to 2019. More recent work highlights practical advances: Information Delivery Specification (IDS) enables machine-readable information requirements and automated checks (buildingSMART International, 2023). IFC 4.3 extends IFC's scope, including infrastructure use cases, and was formalised in recent updates (buildingSMART International, 2024). Recent research (since 2020) finds openBIM mainly in large and infrastructure projects, with limited evidence for smaller ones (Jin & Li, 2023; Fischer et al., 2024).

A broad overview of the possibilities derived from openBIM was published in 2019 (Jiang et al., 2019a, 2019b). The paper thoroughly discusses the topic of openBIM standards and services, including IFC, IDM, MVD, COBie, LandXML, ifcOWL, IFD, BCF, and bSDD. The results show that from January 2000 to October 2019, the IFC was the topic of approximately 78% of all publications related to these standards. The paper highlights that the USA was the leading country in the number of publications, followed by Germany and China. The article also highlights and describes platforms that utilise open standards in BIM, as well as tools supporting open standards that can be implemented in both native and IFC software. It also addresses the topic of information exchange through openBIM participation, demonstrating how openBIM can be utilised in various phases of the construction process. Finally, it identifies research gaps and future directions. One of these is the complexity of defining rules using tools based on Model View Definitions (MVD). It turns out that the answer to this problem is partially the IDS standard, which allows, in an accessible way, to determine what information should be delivered, in what form, and at what stage. The second challenge pointed out is the development of the IFC ontology, which is also being addressed through successive versions of IFC to respond to existing gaps. Considering the above, and taking into account that six years have passed since the publication of this study, it is worth once again summarising the current state of open standards and the benefits resulting from their implementation.

Recent studies confirm the relevance of observations by Jiang et al. (2019a, 2019b) and offer updates on standards and implementation challenges. It is highlighted that openBIM enables a neutral and open environment for exchanging building information, improving interoperability and enabling process integration across disciplines. It is stated that openBIM practices reduce dependency on paid software and enhance collaboration efficiency in project teams working from different locations (Jin & Li, 2023). Similarly,

Fischer et al. (2024) examine the practical adoption of IDS, demonstrating the potential of simplifying the specification of information requirements for regulatory compliance, particularly in permitting workflows. They show that IDS not only addresses the limitations previously associated with MVD but also supports automatic checking, thereby reducing manual review errors. OpenBIM standards collectively contribute to facilitating interoperability throughout the building lifecycle. In particular, a standard IFC model can serve multiple use cases, eliminating the need for separate proprietary formats (Gourabpasi et al., 2025). These research works underline the continuous progress and deepening integration of openBIM standards, emphasising the growing maturity of the ecosystem, as well as the benefits in the AEC sector.

This article discusses key openBIM standards and services, summarising reported benefits and noting challenges or limitations identified in the literature, covering the period of 2020–2025.

Industry Foundation Classes – IFC

IFC is the key BIM data model standard that codifies geometric and non-geometric information about building elements, processes, and stakeholders in a single schema (Yu et al., 2023). Given that it is an ISO standard – ISO 16739 (ISO, 2024) – IFC is supported by most BIM software and viewers, thereby enabling multidisciplinary data exchange without loss of information. Research emphasises that the rich schema of IFC and its ability to work with older versions allow the same model to be used across different phases and disciplines (Yu et al., 2023; Gourabpasi et al., 2025). IFC codifies the identity and semantics (name, unique identifier, building type), characteristics (material, thermal properties), and relationships (locations, ownership) of buildings, processes, and people, creating a consolidated data repository. In practice, the utilisation of IFC enables the connection of design applications with analysis tools, facilitating tasks such as energy simulation by providing an exchangeable format (Yu, Kim, Jeon & Koo, 2023; Gourabpasi et al., 2025). Summarising, IFC enables the use of a standard model and its exchange between disciplines, as well as supporting long-term data reuse.

Despite its benefits, IFC faces notable limitations. Its schema is highly complex, which can lead to inconsistent implementation. Researchers have documented that IFC's underlying EXPRESS-based format (IFC 1.x, 2x2, 2x3, 4.0, 4.1, 4.2) seems to be rigid and not easily adapted to modern data technologies (Yu et al., 2023). It is pointed out that the reliance on EXPRESS reduces IFC's flexibility for partial updates or dynamic data filtering (Yu et al., 2023). It is worth noting that not all software applications fully support the latest IFC schemas (e.g. IFC 4), which can result in interoperability gaps. Furthermore, some domain-specific information (e.g. infrastructure or advanced structural elements) has been missing, requiring extensions or workarounds. This challenge is addressed by the development of IFC 5 and related efforts, which introduce a modular schema and are compatible with XML, JSON, and other formats (Yu et al., 2023). As van Berlo et al. (2021) highlight, IFC 5 aims to modernise the standard by moving away from the rigid EXPRESS syntax and introducing more flexible, modular formats such as JSON and XML, which are more compatible with contemporary IT systems and enable easier integration and partial model updates. Until such updates are widely adopted, project teams may still encounter issues such as incomplete data translations and discrepancies in property set mappings, which hinder the use of IFC, particularly in complex projects.

BIM Collaboration Format – BCF

BCF is a standard for issue tracking and communication across BIM applications. It enables the generation of problem reports, including views, comments, and checkpoints, in a neutral format that can be used by clash detection and model-checking applications (Khemlani, 2021). BCF was developed to streamline reporting clashes and issues to designers without losing context. Its integration with a wide range of BIM software

contributes to the interoperability between multidisciplinary project teams, enabling them to resolve problems rather than communicate them via email correspondence.

BCF's limitations are mostly practical. Regarding the standardisation of usage, different teams may have different workflows for creating BCF reports, leading to potential inconsistencies in how issues are recorded or resolved. Moreover, large and complex projects generating a vast number of BCF issues may cause them to become unwieldy without proper filtering and management tools. Additionally, it should be noted that BCF itself does not contain the model geometry or building data; instead, it includes textual information, screenshots, comments, the location of the issue within the model, and other metadata necessary for coordination among project participants. Therefore, BCF must be used in conjunction with a BIM model, whether in IFC format or a native one.

buildingSMART Data Dictionary – bSDD

bSDD offers industry-specific terminology in a structured format, enabling the linkage of IFC entities to a consistent "classification" or ontology (Yu et al., 2023). The bSDD is a centralised repository of building industry terms: definitions of classes, properties and property sets intended to standardise semantics across projects. By mapping buildings to standardised IFC terms, bSDD enables the BIM data to be consistent and machine-readable (buildingSMART, n.d.-d). By using bSDD, a BIM element can be linked to a unique concept ID, ensuring that it is recognised as the same element type regardless of the software used. Consequently, misunderstandings from synonyms or local codes are eliminated. Moreover, IDS can reference the bSDD dictionary to ensure that requirement definitions align with commonly understood terms (Yu et al., 2023). In this way, bSDD creates a common language for elements, materials, and attributes, enhancing interoperability.

Despite the potential of bSDD, not all software supports automatic linking to bSDD or might only partially integrate it. While bSDD is multilingual and covers many domains, specialised terms or local classifications may not yet exist in the dictionary (Yu et al., 2023). Based on practice-based observations, construction companies often utilise their own classifications during the model creation process and may develop their own Business Support Decision Dictionaries. There is a risk that, instead of linking their classes and properties to existing IFC entities and properties, they may duplicate this data due to naming conventions that differ from those already established in IFC, which is not aligned with the concept of the buildingSMART Data Dictionary.

Information Delivery Specification – IDS

IDS is a standard that specifies information requirements in a machine-readable format. It enables the definition of data that should be delivered by IFC models within a specific development stage and form, thereby contributing to more consistent and verifiable BIM models. The standard represents a significant advancement in formalising and digitising information requirements, addressing previous shortcomings where such requirements were often inconsistent or documented using spreadsheets or PDFs (Tomczak et al., 2022). IDS develops IDM/MVD concepts but packages them into an XML schema to enable automated requirements validation. In practice, using the IDS file enables tagging or validating the IFC export against an IDS and potentially detecting missing data at an early stage. The IDS framework was utilised in recent work to define the minimum data requirements for BIM-to-energy modelling, ensuring the presence of necessary information for simulation tools (Gourabpasi et al., 2025). Fischer et al. (2024) note that IDS is already being used by building authorities for automated code compliance checking and that even small extensions to the IDS schema can expand its applicability. IDS provides the benefit of precise, standardised information delivery, ensuring that the necessary information is included in the BIM model, enabling efficient, error-free data exchange (Fischer et al., 2024).

Being a relatively new buildingSMART standard, it faces some implementation challenges. Defining an IDS for a project requires effort to identify data needs. Additionally, its value depends on the consistent use of classification in the BIM model. The effective use of IDS depends on broader process maturity and integration with tools (Tomczak et al., 2022). The standard still cannot cover specialised use cases – for example, Fischer et al. (2024) found that existing IDS filters were insufficient for certain building permit checks. Having the potential to be implemented in building permit processes, IDS seems to need schema extensions. Limited awareness of IDS among BIM users, along with a lack of familiarity with supporting software, hinders its deployment in the building industry.

Information Delivery Manual – IDM

IDM provides a formal methodology (ISO 29481-1) for capturing and documenting processes and information flows in projects (buildingSMART, n.d.-b). By mapping BIM uses to data requirements, IDM clarifies roles and information needed to be delivered at a particular stage of the construction process. BuildingSMART states that IDM creates a "common understanding" by documenting BIM objectives, use cases, and information exchange requirements. As a benefit, it enhances process coordination, reduces the risk of miscommunication about data responsibilities, and ensures that each exchange follows a consistent structure by clearly defining who should deliver which information, when, and in what format. When combined with the IDS standard, an IDM has the potential to enhance data quality and minimise errors during information transfer. IDM has been successfully utilised to support structured asset data exchanges, for example, in workflows linking BIM to asset management (Farghaly, Abanda, Vidalakis & Wood, 2020). It has also been adapted for prefabricated timber construction, where it helped define process-specific property sets and stakeholder responsibilities (Rojas Wettling, 2023). Recent studies emphasise IDM's ability to map complex post-construction information exchanges, such as those related to existing structures or post-disaster scenarios (Musella et al., 2025).

Although the development of IDM began as early as 2006–2007, the standard remains significantly underutilised in practice, especially when compared to the growing adoption of IDS. Defining an IDM requires substantial early-stage process analysis, which demands both time and commitment at the outset of a project. As a result, many project standards and procedures continue to be documented in informal or unstructured ways, rather than through formalised IDM documentation. It should be noted that IDM often involves modelling processes with specialised software or diagram tools, which can pose an adoption barrier.

Use Case Management – UCM

UCM is a buildingSMART service that integrates best practices and "use cases" across the BIM workflow (buildingSMART, n.d.-e). No peer-reviewed studies from 2020 to 2025 were found that focus solely on UCM; its role is currently documented by buildingSMART documentation, but not addressed in academic literature. UCM utilises the IDM methodology to define and share standardised use cases, processes, and information requirements for tasks from the design to the operational phase. By providing a library of validated use-case templates, UCM supports projects to leverage industry knowledge and accelerates BIM implementation. It supports the openBIM core workflow by reducing the effort required to reinvent process templates and exchange formats for each new project. Instead, it conveys the information about what should happen in each BIM use case, promoting consistency and efficiency across organisations.

As a relatively new initiative, UCM is gaining popularity and acceptance gradually. It depends on active contribution and updating of use cases by the BIM community. Early adopters may appreciate the platform's main features, but widespread adoption requires training and awareness. The practical challenge is to ensure that the use cases remain relevant as the IFC standard evolves. It is worth noting that teams must adapt the published use cases to their specific context. Since UCM is built on IDM, it shares IDM's complexity – creating or selecting the proper use cases requires a deep understanding of project requirements.

Taking into account the research from 2020–2025, IFC is the most thoroughly researched openBIM standard, with extensive analysis and real-world applications. IDS and bSDD are moderately well-studied, whereas BCF and IDM receive less attention, and UCM appears to be the least examined in the academic literature. The existing research proves that openBIM standards and services provide clear benefits in promoting interoperability, data consistency, and coordination across the AEC industry (Yu et al., 2023; Gourabpasi et al., 2025). Each standard or service brings advantages: IFC – comprehensive schema, BCF – issue tracking, bSDD – standard semantics, IDS – specification of deliverables, IDM – clarity of the process, and UCM – use-cases templates. However, the literature from 2020–2025 also highlights challenges, including the technical limitations of schemas (IFC), the evolving implementation of newer tools (IDS, UCM), and the need for organisational change to leverage these standards fully. By understanding these benefits and hurdles, practitioners can better integrate openBIM into projects for more efficient and reliable data exchange.

RESULTS AND DISCUSSION

Results – case study

In this case study, we demonstrate the practical implementation and integration of openBIM standards using a BIM model for a conceptual museum building based in Warsaw, Poland. The model included architecture, structure, and ventilation systems, which allowed for the demonstration of interdisciplinary collaboration between architect, structural engineer, and MEP engineer within an openBIM workflow. The architectural model was created in ArchiCAD, exported to the IFC 4 format, and then processed in the Blender application, using the Bonsai extension. The aim was to apply and verify the use of the openBIM standards: IFC, BCF, bSDD, IDS, IDM, and UCM. For the purposes of this case study, a demonstration was performed in the IfcWall class. The same properties and validation logic presented below could be analogously applied to other IFC entities; these were not repeated to avoid redundancy.

Step 1: Creation of the classification as a bSDD dictionary

At the beginning, the custom classification for the building was created as a dictionary (in JSON format), based on the buildingSMART Data Dictionary (bSDD) with the usage of usBIM.bSDDeditor from ACCA. This platform allows the creation of a JSON file without knowing programming languages.

The bSDD service enables the user to search for a dictionary. The published *Construction Process Dictionary*, where the demonstration class (‘Wall’) is mapped to the ‘ifcWall’ entity, and the property sets contain attributes relevant throughout the entire construction process. The properties are grouped into the following property sets: ‘01_Identification Data’, ‘02_Quantity Data’, ‘03_Location Data’, ‘04_Common Element Properties’, ‘05_Phase Data’, ‘06_Execution Data’, ‘07_Maintenance Data’, ‘08_Sustainability Data’, and ‘09_Demolition Data’. Then the bSDD was downloaded from the platform in a JSON file and uploaded to the bSDD service using the buildingSMART manage platform.

Step 2: Importing the IFC model and applying bSDD classification in Blender

The architectural model of the museum building was exported to IFC format and imported into the Blender application. The Bonsai extension was used to manage classification and property sets in compliance with the openBIM methodology. The custom classification dictionary (in JSON format) based on the buildingSMART Data Dictionary was loaded into Blender using the Bonsai interface (Fig. 1). Then, a wall element (IfcWall) was selected. The corresponding bSDD class (Wall) was assigned, thereby automatically assigning all properties and property sets previously defined in the bSDD with references to standardised names, codes, and data types. Subsequently, the values of the above-mentioned parameters were filled in (Fig. 2).

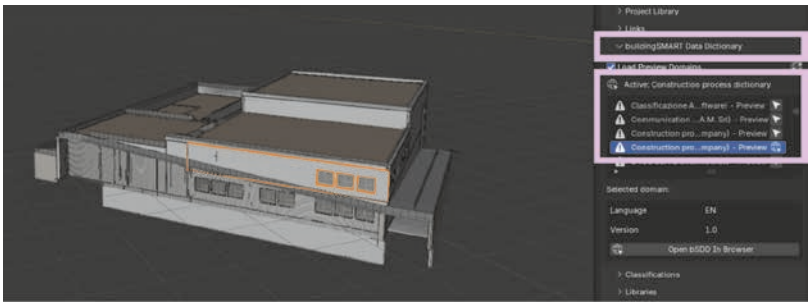


Fig. 1. Loading the bSDD dictionary into the Blender application with the usage of the Bonsai plug-in

Source: own work.

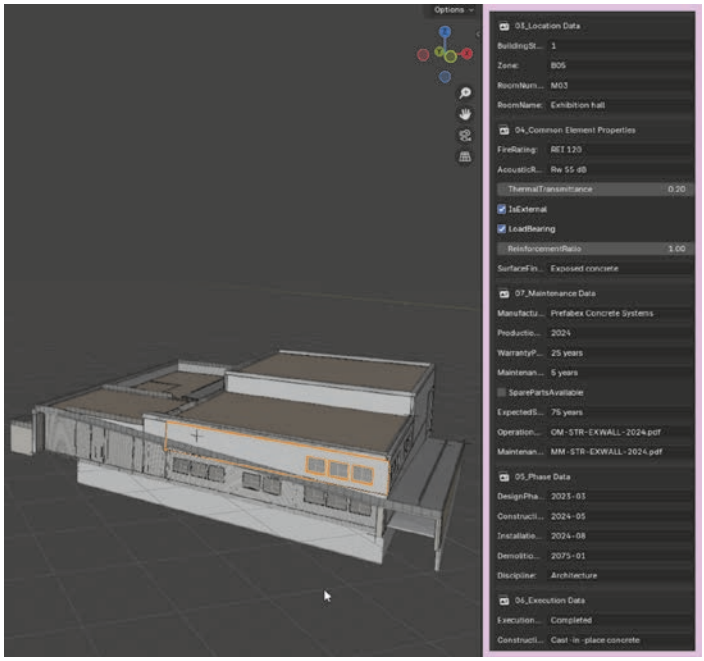


Fig. 2. Property sets and properties defined in bSDD are filled in with proper values

Source: own work.

Step 3: Creating IDS specifications for model validation

A single IDS file (in XML format) was created to validate multiple information requirements for a selected wall element. This step aimed to validate whether the information requirements defined in the bSDD file were correctly fulfilled within the IFC file. The IDS specification was created using IDS Maker by Datacomp IT, which enables the creation of IDS specifications without requiring programming skills. First, the metadata was defined. The file included three specifications: validation rules aimed at checking property presence, correct data types, and value formatting, as detailed below. The IDS file targeted the 'IfcWall' entity and includes a filter, restricting validation to a single element based on its GlobalId 2MHs2GzN5FdhzT1r$zhAjO,

which was defined in the 'Applicability' section of each of the specifications. Then, the 'Requirements' sections were described, aimed at performing the following checks:

1. Presence and data type validation: for the property 'BuildingStorey' within the property set '03_Location Data'. The requirement ensures that the selected wall contains the Building Storey property and that its value is represented as a string.
2. Controlled vocabulary and data type validation: for the property 'FireRating' within the property set '04_Common Element Properties'. The property value is expected to follow the official REI fire resistance rating system (e.g. REI 30, REI 60, REI 90, REI 120, REI 180), represented as a string. Values that deviate from this convention are considered invalid. The specification lists the allowed values as an enumeration and requires formatting with a space (e.g. REI 120).
3. Pattern-based validation: for the property 'AcousticRating' within the property set '04_Common Element Properties'. The requirement enforces that the property value is of IfcLabel type and must conform to a specific text format: 'Rw XX dB', where XX represents a two-digit number. This format is validated using a regular expression pattern: '^Rw\s\d{2}\sdB$'. The pattern checks that the value starts with 'Rw', followed by a space, two digits, another space, and ends with 'dB'. This ensures standardised acoustic rating syntax across the model.

Step 4: Validating the model using IDS in Blender

As a final step, the IDS file (in XML format) was downloaded from the platform and imported into Blender via the Bonsai interface using the 'Quality and Coordination' and 'IFC Tester' panels (Fig. 3).

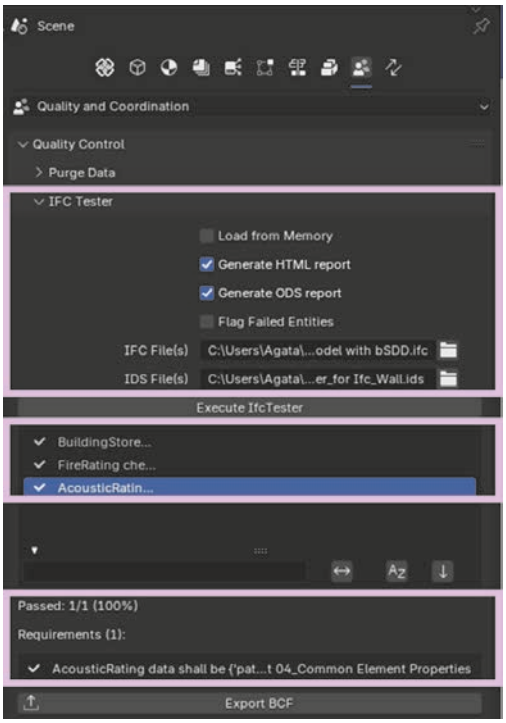


Fig. 3. The museum BIM model classification validation with the usage of the IDS file – the model successfully passed the verification process

Source: own work.

The model passed all three validation checks defined in the IDS file. The model confirmed the presence and correct typing of 'BuildingStorey', compliance with the REI fire rating list in 'FireRating', and proper formatting of 'AcousticRating' according to the expected regular expression pattern. Additionally, an HTML report was created that included detailed information about the validation. This step demonstrates the practical capability of IDS to automatically validate data consistency and regulatory compliance directly within an openBIM environment.

Step 5: Creating and exporting a BCF file

Had the model contained validation errors – such as a missing required property or a value that did not conform to the expected format – a BCF file could have been created directly within Blender using the Bonsai interface, directly after the IDS file validation (Fig. 3). In the case study, the BCF export was presented as a theoretical example, as the validation files created for the demonstration did not contain errors. The resulting BCF file would typically include: metadata such as the author of the comment, issue status and priority level, a screenshot capturing the specific model view where the issue is visible, and a markup file containing the issue description, comments, and the reference to the relevant building using its GlobalId. Such a BCF file could then be shared with the project team via a Common Data Environment (CDE) platform or BIM coordination platform. This would enable structured, transparent issue tracking and resolution, independent of the software used. Even though the discussed model passed all IDS-based validation checks successfully, this method shows how BCF supports openBIM-based workflows when data inconsistencies are detected in Step 4.

Step 6: Representing information flows using IDM

In this step, the IDM was conceptually applied to define who creates and delivers which openBIM files – such as IFC models for geometry and data, IDS for validation requirements, BCF for issue tracking, and bSDD-based property definitions – at each stage of the coordination workflow. The IDM mapping explicitly reflected interactions between the Architect, Structural Engineer, MEP Engineer, and BIM coordinator, illustrating the collaborative workflow rather than a purely theoretical structure. Specifically, IDM principles were used to identify the responsibilities of each discipline – architect, structural engineer, and engineer – during the design development stage. Each discipline is responsible for providing correct IFC models, including classification and performance properties, according to the buildingSMART Data Dictionary, previously prepared by the BIM coordinator. Although IDM is not a software tool, it provides a clear structure that helps organise the information flow by defining what data needs to be shared, by whom, and when. This conceptual structure guided the development of the Business Process Model and Notation (BPMN) process diagram, which represents the part of the openBIM flow described in the case study. The BPMN process (Fig. 4) visually represents the coordination workflow for validating IFC models against IDS files. These IDS files reference bSDD-defined properties to ensure that all required attributes are correctly delivered. Each participant (architect, structural engineer, MEP) first prepares and exports their IFC model, which is then uploaded to the CDE platform. Secondly, the BIM coordinator uses the IDS to validate each discipline's IFC model. If validation fails, a BCF issue is generated and sent to the responsible discipline for correction, ensuring traceability. The corrected model is then re-validated in a loop until all information meets the defined requirements. If no issues are found, the process ends. In this way, IDM provides the foundation for the logical structure and responsibilities embedded in the BPMN workflow. The process map illustrates the practical application of IDM principles utilising interoperable openBIM standards and services, in alignment with buildingSMART recommendations. This contributes to both data consistency and multidisciplinary interoperable coordination, enhancing efficiency throughout the design process.

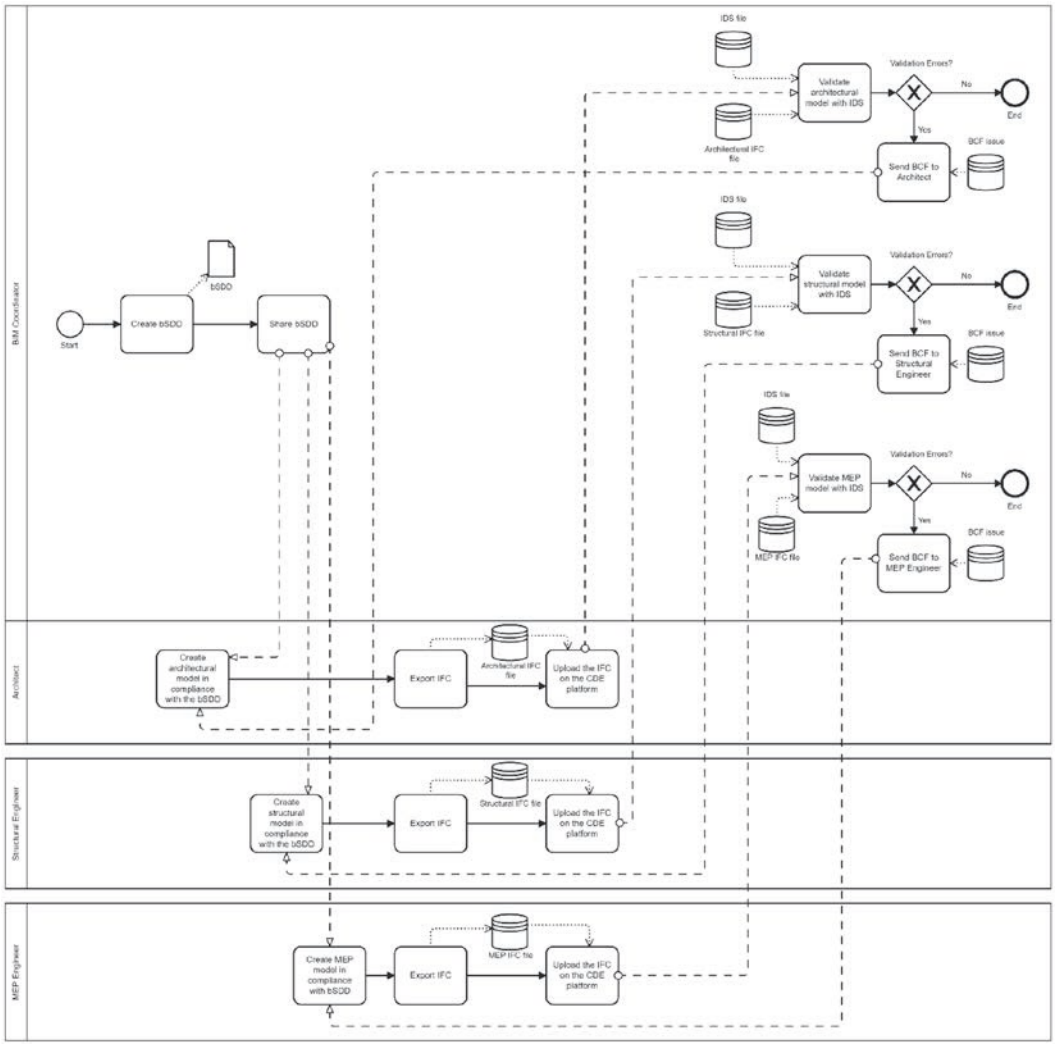


Fig. 4. BPMN process map for BIM model validation and coordination based on IDM principles

Source: own work.

Step 7: Applying UCM to structure information validation and coordination

In the final step of the case study, the UCM framework developed by buildingSMART was applied to structure and document the information flows, responsibilities, and validation logic already established in the previous steps using IDM and BPMN. As mentioned, UCM provides a framework to formalise project objectives and outcomes by aligning them with standard, reusable, openBIM workflows. Instead of creating a fully custom UCM, this step adopted the existing use case, *BCF & Issue Management from Building Owners* (buildingSMART International, 2023), available on the buildingSMART UCM platform. This existing use case reflects the process described in Step 6: IFC model validation using the IDS file, with a special focus on issues that are communicated through BCF for resolution. This approach supports the UCM's fundamental goal of reusing well-established, community-validated workflows to ensure implementation efficiency.

The selected UCM use case highlights the use of BCF for managing and communicating issues. It illustrates how BCF facilitates transparent issue tracking and resolution among project stakeholders. The advantages of referencing this UCM use case include a better understanding of how BCF supports communication, documentation, and resolution of issues, as well as clarification of responsibilities related to issue management and alignment of the project workflow with an established example of BCF usage. This example illustrates the practical application of BCF within the broader openBIM framework, enhancing collaboration and interoperability.

Table 1 summarises the practical steps applied in the case study and illustrates how each openBIM standard contributes to the overall workflow. The sequential integration of bSDD, IFC, IDS, BCF, IDM, and UCM demonstrates not only their individual benefits but also their cumulative effect on improving interoperability, ensuring data quality, and enhancing interdisciplinary coordination.

Table 1. Case study stages and highlighted benefits

Stage	Description	Benefits
1. bSDD classification	Creation of a custom classification dictionary in compliance with the buildingSMART Data Dictionary and its application to IFC entities.	Ensures semantic consistency, standardised terminology, and machine-readability of BIM data.
2. IFC model import	Import of the architectural model into Blender and assignment of bSDD-based classifications and properties.	Enables open, vendor-neutral model transfer and unified data environment.
3. IDS specification	Preparation of IDS rules in XML format to check the presence, types, and formatting of required attributes.	Allows automated validation of model data, ensuring completeness and compliance with requirements.
4. IDS-based validation	Execution of validation rules on the IFC model using Blender's Bonsai extension.	Detects inconsistencies early, reduces errors, and generates structured validation reports.
5. BCF export	Generation of BCF issue reports in case of non-compliance detected during validation.	Facilitates transparent communication and efficient issue tracking between stakeholders.
6. IDM workflow	Definition of roles, responsibilities, and information flows using IDM principles and BPMN diagrams.	Provides clarity of process, reduces miscommunication, and structures interdisciplinary collaboration.
7. UCM use case	Adoption of a standardised UCM template reflecting issue management workflows.	Supports reuse of best practices, accelerates BIM implementation, and ensures alignment with industry standards.

Source: own work.

In the presented case study, the UCM framework was applied at a conceptual level to structure and document information validation and coordination tasks. Although the project was not realised, the adoption of existing UCM templates, such as *BCF & Issue Management from Building Owners*, demonstrates how openBIM use cases can be standardised and reused across projects. In a realised design process, UCM would serve as a bridge between theoretical process mapping (IDM) and practical project execution by providing templates that clarify responsibilities, define data exchanges, and guide the resolution of issues at each stage. For example, during detailed design or construction design phases, UCM templates could support clash detection workflows by standardising the way BCF reports are created, shared, and resolved among disciplines. This illustrates the potential of UCM not only to document best practices but also to formalise interdisciplinary collaboration, making the workflow repeatable and transferable to different project contexts.

In the Polish context, legal and implementation issues continue to pose a significant challenge to openBIM adoption. Although BIM is increasingly promoted through governmental and industry initiatives, there is still no binding national regulation that mandates the use of open standards such as IFC or IDS. Current public procurement law allows BIM to be required in tenders; however, in practice, these requirements are often formulated in diverse and inconsistent ways, sometimes tied to proprietary formats rather than open ones. This creates uncertainty for contractors and designers, limiting the comparability of deliverables. Furthermore, the lack of official national guidelines on openBIM workflows means that implementation depends mainly on the policies of individual organisations and their level of digital maturity. As a result, although technical solutions are available, Poland's legal frameworks and procurement practices still need to evolve to support the systematic and large-scale use of openBIM.

CONCLUSIONS

OpenBIM standards collectively enhance interoperability and project efficiency by providing a unified framework for data exchange (Ren, Zhang & Müller, 2025). The literature emphasises that IFC-enabled model federation reduces data fragmentation across disciplines (Jiang et al., 2019a, 2019b), while BCF supports issue tracking (Khemlani, 2021). The usage of bSDD ensures semantic consistency (Oraskari, 2021), and IDS has the potential to formalise project requirements for automated validation (Fischer et al., 2024; Gourabpasi et al., 2025). IDM clarifies workflows and exchange requirements (Kim et al., 2010; Rojas Wettling, 2023), while UCM promotes the reuse of proven coordination workflows (Musella et al., 2020). The presented case study confirmed these benefits in practice. An IFC model, enhanced with bSDD-based classification, served as an information-rich asset that could be exchanged among different stakeholders throughout the construction process due to its open, non-proprietary format. IDS-based validation rules automatically checked required properties, and any discrepancies were documented in BCF issue reports and could be resolved within a workflow defined in IDM. Finally, the use of UCM demonstrated the feasibility of formalising and reusing standardised use cases, thereby supporting the consistent implementation of openBIM practices across projects. The case study as a whole shows how the coordinated use of openBIM standards and services enhanced model quality and interdisciplinary collaboration, ultimately reducing errors and facilitating the acceleration of information exchange throughout the project lifecycle. In addition to the technical aspects demonstrated in the case study, organisational barriers remain a key challenge for the wider adoption of openBIM. The need for clear allocation of responsibilities, appropriate contractual frameworks, and investment in user training shows that efficiency gains depend not only on interoperable standards but also on organisational readiness to implement them.

Key strengths include improved data consistency, increased access to project information, and faster issue resolution through automated validation. However, challenges emerged: many tools still lack full support for newer standards (Yu et al., 2023), requiring manual workarounds and user training. Some technical limitations persist, e.g. complex elements are not fully supported in IFC (Ren et al., 2025). These observations align with reviews noting that openBIM adoption is hindered by schema complexity and evolving toolchains (Tomczak et al., 2022). Future research could test these integrated workflows across broader project phases, from design through operation. Integrating openBIM with digital twins, GIS, and other systems will also be crucial (Ren et al., 2025). As a roadmap for future work, further testing in real-life projects is planned, including the application of IFC 4.3, developing domain-specific extensions or MVDs, and improving support for IDS and UCM (van Berlo et al., 2021; Yu et al., 2023). These steps will facilitate the adoption of openBIM and enhance data integration throughout the project lifecycle.

A limitation of the present research is that the case study was based on a conceptual, not realised, design. This allowed us to test interoperability and data validation mechanisms in a controlled environment, but did

not include the full scope of the design and construction process. Consequently, while the study demonstrates improvements in interdisciplinary collaboration and clash detection at the design stage, it cannot fully address later phases such as detailed design, implementation, and operation. Future research should therefore apply the integrated openBIM workflow (IFC, bSDD, IDS, BCF, IDM, UCM) to realised projects, in order to evaluate their impact across the entire lifecycle. Such studies would enable a realistic assessment of how openBIM services improve coordination, support clash detection, and facilitate data exchange under practical project conditions, thereby providing stronger evidence for the hypothesis formulated in this paper.

The case study illustrates that the integration of openBIM standards brings measurable improvements in model quality, coordination, and communication. In particular, bSDD and IDS ensured consistency and completeness of information before coordination meetings, reducing the likelihood of misinterpretation. The possibility of automatically validating properties such as fire resistance or acoustic rating shows how rule-based checks can substitute time-consuming manual reviews. Although the presented project was conceptual, the workflow proved that even at early design stages, structured classification and validation significantly reduce potential coordination issues.

A key added value was the demonstration of interoperability: architectural, structural, and MEP models created in different authoring tools were combined in IFC format, without data loss. This confirms the role of IFC as a neutral backbone for cross-disciplinary collaboration. Moreover, the complementary use of IDS and BCF illustrated how information requirements and issue management can be tightly connected, creating a closed feedback loop between validation and correction. Such integration addresses one of the most common pain points in practice – the fragmentation of information across emails, spreadsheets, and proprietary tools.

Nevertheless, the case study also revealed current limitations. The practical use of IDS and UCM requires higher process maturity and tool support than is currently available in many organisations. While the theoretical benefits are clear, their full potential depends on awareness, training, and wider adoption across the AEC industry.

The study does not focus on implementation costs; however, for clarity, typical cost categories that affect openBIM adoption should be outlined: setup costs (software licenses, hardware upgrades, initial consultancy, configuration), training and competence development, per-project modelling and validation effort (person-hours), CDE/subscription fees, and ongoing maintenance. At the same time, openBIM can reduce costs compared to native solutions, since expensive commercial model viewers are not required, and several IFC-based viewers are available free of charge. Future studies should report costs and compare them to estimated savings from reduced work, fewer coordination efforts and automation of checks.

While openBIM standards can be applied across a variety of project types, their benefits are most pronounced in large-scale and complex projects, particularly under design-and-build contracts, where multidisciplinary coordination and consistent data exchange are critical. Future research could also address the applicability and value of openBIM in smaller projects.

The coordinated use of openBIM standards in the case study confirmed that information consistency and automated validation directly improve collaboration and reduce the risk of errors. The added discussion highlights that the benefits are most visible in interdisciplinary coordination, where common classification, automated checks, and structured issue management accelerate the resolution of conflicts and enhance trust in shared models.

Although based on a conceptual project, the presented workflow demonstrates a repeatable methodology that can be adapted to realised projects. Therefore, the findings provide not only theoretical insights but also practical guidelines for practitioners aiming to implement openBIM in design coordination. With further development of tools and wider industry training, the tested approach has the potential to significantly improve efficiency and data reliability throughout the building lifecycle.

REFERENCES

Berlo, L. van, Krijnen, T., Tauscher, H., Liebich, T., Kranenburg, A. van & Paasiala, P. (2021). Future of the industry foundation classes: Towards IFC 5. In *Proceedings of the 38th International Conference of CIB W78, Luxembourg, 11–15 October 2021* (pp. 123–137).

Borgos, K. S. (2022, July 5). *Digitalisation use case*. ISO/TC 59 Buildings and Civil Engineering Works. Retrieved from: https://committee.iso.org/sites/tc59/home/news/content-left-area/news-and-updates/digitalisation-use-case.html [accessed: 15.06.2025].

buildingSMART (n.d.-a). *IFC – Industry Foundation Classes*. Retrieved from: https://www.buildingsmart.org/standards/bsi-standards/industry-foundation-classes [accessed: 11.06.2025].

buildingSMART (n.d.-b). *Information Delivery Manual (IDM).* Retrieved from: https://www.buildingsmart.org/standards/bsi-standards/information-delivery-manual-idm [accessed: 11.06.2025].

buildingSMART (n.d.-c). *Information Delivery Specification (IDS)*. Retrieved from: https://www.buildingsmart.org/standards/bsi-standards/information-delivery-specification [accessed: 11.06.2025].

buildingSMART (n.d.-d). *buildingSMART Data Dictionary (bSDD)*. Retrieved from: https://www.buildingsmart.org/standards/bsi-standards/buildingsmart-data-dictionary [accessed: 11.06.2025].

buildingSMART (n.d.-e). *Use Case Management Service (UCM)*. Retrieved from: https://www.buildingsmart.org/users/services/use-case-management-service/ [accessed: 11.06.2025].

buildingSMART International (2010). *IDM Guide to Components and Development Methods (IDMC_004, v1.2)*. Retrieved from: https://standards.buildingsmart.org/documents/IDM/IDM_guide-CompsAndDevMethods-IDMC_004-v1_2.pdf [accessed: 25.06.2025].

buildingSMART International (2013a). *IDM Word Template for Exchange Requirements*. Retrieved from: https://standards.buildingsmart.org/documents/IDM/IDM_template-ProcessMaps.docx [accessed: 25.06.2025].

buildingSMART International (2013b). *IDM Word Template for Functional Parts*. Retrieved from: https://standards.buildingsmart.org/documents/IDM/IDM_template-FunctionalParts.docx [accessed: 25.06.2025].

buildingSMART International (2023). *BCF & Issue Management from Building Owners and Sustainability Consultants Perspective.* buildingSMART UCM. Retrieved from: https://ucm.buildingsmart.org/use-case-details/2518/en [accessed: 25.06.2025].

buildingSMART International (2025). *Guidelines for creating a data dictionary*. Retrieved from: https://technical.buildingsmart.org/services/bsdd/guidelines/ [accessed: 15.06.2025].

Farghaly, A., Abanda, F. H., Vidalakis, C. & Wood, G. (2020). BIM-enabled asset management information exchange: IDM/MVD approach. *Buildings*, *10* (12), 239. https://doi.org/10.3390/buildings10120239

Fischer, S., Urban, H., Schranz, C., Loibl, P. & Berlo, L. van (2024). Extending Information Delivery Specifications for digital building permit requirements. *Developments in the Built Environment*, *20*, 100560. https://doi.org/10.1016/j.dibe.2024.100560

Gourabpasi, A. H., Jalaei, F. & Ghobadi, M. (2025). Developing an openBIM Information Delivery Specifications Framework for operational carbon impact assessment of building projects. *Sustainability*, *17* (2), 673. https://doi.org/10.3390/su17020673

International Organization for Standardization [ISO] (2016). *Building information models – Information delivery manual. Part 1: Methodology and format* (ISO 29481-1).

International Organization for Standardization [ISO] (2024). *Industry Foundation Classes (IFC) for data sharing in the construction and facility management industries* (ISO 16739).

Jiang, L., Yu, Y. & Guo, X. (2019a). Overview of openBIM standards and services: Status and trends. *Automation in Construction*, *102*, 20–31.

Jiang, S., Jiang, L., Han, Y., Wu, Z. & Wang, N. (2019b). OpenBIM: An enabling solution for information interoperability. *Applied Sciences*, *9* (24), 5358. https://doi.org/10.3390/app9245358

Jin, M. & Li, B. (2023). A dual-level framework for openBIM-enabled design collaboration. *Buildings*, *13* (12), 3031. https://doi.org/10.3390/buildings13123031

Khemlani, L. (2021, February 11). An overview of buildingSMART standards. *AECbytes*. Retrieved from: https://www.aecbytes.com/feature/2021/BuildingSMARTstandards.html [accessed: 01.09.2025].

Kim, C., Kwon, S., You, S. & Lim, J. (2010). Using Information Delivery Manual (IDM) for efficient exchange of building design information. In *Proceedings of the 27th International Symposium on Automation and Robotics in Construction* (pp. 490–497). International Association for Automation and Robotics in Construction. https://doi.org/10.22260/ISARC2010/0052

Musella, C., Serra, M., Salzano, A., Menna, C. & Asprone, D. (2020). Open BIM standards: A review of the processes for managing existing structures in the pre- and post-earthquake phases. *CivilEng*, *1* (3), 291–309. https://doi.org/10.3390/civileng1030019

Oraskari, J. (2021). Live Web Ontology for buildingSMART Data Dictionary. In *32. Forum Bauinformatik 2021* (Vol. 32, pp. 166–173). Technische Universität Darmstadt. https://doi.org/10.26083/tuprints-00019496

Ren, Y., Zhang, H. & Müller, C. (2025). Integration of openBIM with digital twins and GIS for enhanced data interoperability in construction. *Journal of Construction Informatics*, *31* (2), 145–162. https://doi.org/10.1016/j.jci.2025.02.004

Rojas Wettling, A. (2023). IDM for the conceptual evaluation process of industrialized timber projects. *Journal of Building Performance*, *14* (1), 36–50. https://doi.org/10.1002/btp2.172

Tomczak, A., Berlo, L. van, Krijnen, T., Borrmann, A. & Bolpagni, M. (2022). A review of methods to specify information requirements in digital construction projects. *IOP Conference Series: Earth and Environmental Science*, *1101* (9), 092024. https://doi.org/10.1088/1755-1315/1101/9/092024

Yu, Y., Kim, S., Jeon, H. & Koo, B. (2023). A systematic review of the trends and advances in IFC schema extensions for BIM interoperability. *Applied Sciences*, *13* (23), 12560. https://doi.org/10.3390/app132312560

BADANIE KORZYŚCI PŁYNĄCYCH ZE STANDARDÓW openBIM W ZAKRESIE ZWIĘKSZONEJ INTEROPERACYJNOŚCI I EFEKTYWNOŚCI W PROJEKTACH ARCHITEKTONICZNO-BUDOWLANYCH

STRESZCZENIE

W artykule przeanalizowano wpływ standardów openBIM na interoperacyjność i efektywność w projektach budowlanych. Przyjęto hipotezę, że skoordynowane zastosowanie standardów i usług openBIM, takich jak: IFC, BCF, bSDD, IDS, IDM i UCM, poprawi jakość informacji oraz zmniejszy liczbę błędów podczas koordynacji międzybranżowej. Metodologia łączy przegląd literatury z praktycznym studium przypadku koncepcyjnego modelu BIM budynku muzeum. Wyniki wskazują, że każdy standard odgrywa odrębną rolę: IFC umożliwia jednolity transfer modeli, BCF ułatwia rejestrowanie problemów, bSDD zapewnia ustandaryzowaną semantykę, IDS umożliwia automatyczną weryfikację danych, IDM usprawnia przepływ informacji między stronami procesu, a UCM pozwala utrwalać i ponownie wykorzystywać dobre praktyki. Wspólnie wymienione standardy usprawniają wymianę danych, poprawiają koordynację i zmniejszają liczbę błędów. Do wyzwań należą: ograniczone wsparcie narzędziowe i potrzeba szkolenia użytkowników. Podsumowując, standardy openBIM wspierają współpracę i efektywność; istnieje również potrzeba dalszych badań nad ich praktyczną implementacją.

Słowa kluczowe: architektura, projekt, openBIM, IFC, bSDD, IDS

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CONTEMPORARY DESIGN OF SUSTAINABLE CAMPUS SPACES: A CASE STUDY OF THE EXTENSION OF THE WATER CENTRE AT THE WARSAW UNIVERSITY OF LIFE SCIENCES – SGGW

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ABSTRACT

The paper examines the role of sustainable and participatory design in modernising university campuses, focusing on the extension of the Water Centre at the Warsaw University of Life Sciences – SGGW. The study explores integrating pro-ecological strategies, including green roofs, rainwater recirculation, renewable energy systems, and student engagement in spatial planning. The research evaluates how these interventions enhance campus functionality, user well-being, and environmental resilience through a case study approach. The findings indicate that sustainable campus redevelopment improves microclimatic conditions and biodiversity, as well as fostering inclusivity and academic community engagement. The paper contributes to the discourse on ecological urbanism and the adaptation of educational spaces to contemporary sustainability challenges.

Keywords: sustainable design, campus infrastructure, blue-green solutions, university architecture

INTRODUCTION

Modern university campuses face increasing challenges in balancing sustainability with the evolving needs of academic communities. In the context of rapid urbanisation, climate change, and shifting societal expectations, campus spaces must go beyond their traditional educational and research roles to enhance user well-being and promote social inclusion (Jakimiuk et al., 2023; Vaverková et al., 2024). A crucial aspect of contemporary campus planning is the integration of environmentally friendly, energy-efficient solutions and the active involvement of students and staff in the design process (Moscoso et al., 2024).

In response to these challenges, the design team proposed many innovative solutions as part of the project to extend and modernise the Water Centre at the Warsaw University of Life Sciences – SGGW (in short: the Water Centre) (Zagrajek et al., 2023). This study examines the redevelopment and expansion of the Water Centre as a case study in sustainable campus modernisation. The project introduces multiple pro-ecological strategies, including green roofs, rainwater retention and recirculation, photovoltaic panels, and the use of innovative building materials (Stefańska et al., 2023). The redesign also emphasises accessibility,

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with improved facilities for people with disabilities and the creation of diverse communal areas for learning, recreation, and social interaction (Kulpa-Puczyńska, 2022).

Revitalising the surroundings of the Water Centre was also an essential part of the project. Green spaces were designed to encourage biodiversity and adaptation to climate change. A system of pedestrian and cycle paths was introduced, linking the main arteries of the campus, as well as microhabitats for insects and small animals. Greenery was supplemented with shrubs (including formally pruned shrubs) and trees to provide year-round appeal and blue-green infrastructure elements such as infiltration troughs and flower meadows.

Beyond architectural interventions, the revitalisation of the Water Centre's surroundings plays a pivotal role in enhancing campus resilience. Introducing pedestrian and cycling infrastructure, biodiversity-promoting microhabitats, and blue-green infrastructure, such as infiltration troughs and rain gardens, supports climate adaptation while fostering a dynamic, user-friendly environment. These elements align with broader urban sustainability principles, demonstrating how ecological and participatory design can shape modern academic landscapes (Zhong, Schroeder & Bekkering, 2022; Ibiyeye, Shamang & Malachy, 2024).

The interventions implemented in the Water Centre extension are consistent with several established theoretical frameworks. Elements such as biodiverse microhabitats, rainwater management, and natural light optimisation resonate with the principles of biophilic design, which emphasises the integration of natural systems into the built environment to improve health and well-being (Zhong et al., 2022). At the same time, the reuse of materials and reliance on renewable energy sources correspond to the logic of the circular economy, where resource cycles are closed, and waste is minimised (Łacek & Starzyk, 2023). By situating the case study within these frameworks, the paper contributes to bridging design practice with ecological urbanism theory, highlighting how campus redevelopment can serve as a testbed for sustainable innovation.

This paper analyses the impact of these interventions on campus functionality, user experience, and sustainability performance. Emphasis is placed on the role of blue-green infrastructure in improving microclimatic conditions and student engagement in shaping their academic environment. By contextualising this case study within global trends in sustainable campus design, the study contributes to the discourse on resilient and inclusive university spaces.

Science and university facilities

The expansion of science facilities on university campuses presents significant urban, architectural, and environmental challenges. Contemporary processes for modernising such buildings consider functional aspects, user needs and sustainability challenges. The main directions of redevelopment include improving energy efficiency, revitalising common spaces and implementing intelligent building management systems. User participation in the design process and the adaptation of spaces to modern standards of comfort and ergonomics also remain key aspects. The successful modernisation of campus facilities requires a holistic approach, combining advanced technologies, user comfort and sustainability principles. Key strategies include flexible, collaborative spaces, energy efficiency, integrated management systems and optimising environmental conditions.

Recent scholarship increasingly frames campus redevelopment as part of broader sustainability transitions. For instance, biophilic design provides a conceptual lens to evaluate how green roofs, natural ventilation, or vertical greenery influence both environmental performance and user experience. Similarly, the circular economy perspective emphasises adaptive reuse of materials and systems thinking in managing energy and water flows. By engaging these frameworks, the present study positions the Water Centre as not only a functional upgrade but also as a demonstrator of how theoretical concepts can be operationalised in academic infrastructure.

Existing studies of campus redevelopment often emphasise single dimensions of sustainability, such as energy efficiency or user participation. However, fewer works explicitly demonstrate how multiple

frameworks can be operationalised in a coherent design process. For example, while biophilic design reviews highlight health and well-being benefits, they rarely address how these strategies interact with circular economy principles of resource reuse. Similarly, ecological urbanism remains largely conceptual without detailed application to campus infrastructure. By synthesising these strands, the Water Centre case contributes to closing this gap and illustrates the combined application of these frameworks in a university setting.

The Massachusetts Institute of Technology's MIT.nano is an advanced research complex dedicated to nanotechnology and materials engineering. The expansion project focused on integrating laboratory spaces with open, collaborative areas, allowing interdisciplinary research teams to use the building flexibly. A key aspect of the upgrade was implementing energy-efficient heating, ventilation, and air conditioning (HVAC) systems and improved thermal insulation, helping reduce the facility's carbon footprint. The design also incorporated high-quality natural lighting and acoustic optimisation of the space, which improved user comfort.

The Nanyang Technological University has comprehensively refurbished its teaching facilities, emphasising climate change adaptation and energy efficiency improvements. The retrofitted buildings received new façades with vertical vegetation, helping to reduce the urban heat island effect. Artificial intelligence-based energy management systems were used, as well as modular teaching spaces that can be adapted to different teaching forms. In addition, the buildings were equipped with natural ventilation systems, which significantly reduced operating costs.

The Groningen Forum is a multifunctional academic facility that combines educational, research, and recreational spaces. Modernisation focused on restructuring the functional layout and creating a more accessible and interactive public space. Green roofs, outdoor terraces, and advanced rainwater retention systems were introduced, significantly improving the microclimate around the building. The open spatial concept has created a conducive environment for individual and collaborative work, increasing student and academic staff satisfaction.

MATERIAL AND METHODS

The Water Centre redevelopment project was analysed as a case study to illustrate the implementation of sustainable and participatory design principles for campus spaces. The execution of the redevelopment concept was the subject of an internal competition for staff, PhD students, and university students. Three mixed teams were selected, including representatives of the above groups in the interdisciplinary community of architects, builders, and landscape architects.

The pre-project research was based on a two-step analysis, including:

1. A two-day workshop with architectural student representatives present, which resulted in a detailed SWOT (strengths, weaknesses, opportunities, and threats) analysis that set the direction of further conceptual work.
2. Detailed analysis of the project documentation, which included a functional and spatial plan, environmental and energy solutions, landscaping, and adaptation of the space to the needs of people with disabilities. The documentation also provided details of the social infrastructure, including new recreational zones, exhibition spaces, and group work areas.

The materials were complemented by consultations with campus users, students, and academic staff, which took the form of pre-architectural competition participants' evaluations in each team. This enabled a broader view in the form of expectations and preferences regarding the designed space to be considered.

A mixed methodological approach was used, combining qualitative and quantitative analyses. The study analysed the design documentation, focusing on the sustainable solutions implemented, their compliance

with the urban design guidelines, and the latest pro-ecological and pro-climate trends prevailing in shaping open spaces. An assessment of the preservation state of existing greenery was also carried out, and design guidelines were proposed to increase biodiversity and improve water relations through rainwater management (Wichowski, Rutkowska, Kamiński & Trach, 2019) and nature-based solutions (NbS). At the same time, the anticipated energy savings from the building management system (BMS) were assessed. The Water Centre is a building with modern insulation, built less than two decades ago, which allows a BMS system to operate efficiently without energy loss through the external walls, roof, or foundation. A BMS system is usually designed during the later phases of building development. The conceptual design sets the goals, while the executive design describes and specifies the technical parameters. Because the building management system controls every technical installation in the building, the planned energy savings can be further enhanced through well-organised control of energy flows during the building's operation and maintenance. Kamali, Khakzar and Abdali Hajiabadi (2013) describe a case study of a 20-year-old office building in San Francisco, USA, with a floor area of 66,943 ft². After implementing a BMS regulation system, the building achieved an average annual energy reduction of 50%. The paper by Colmenar-Santos, Terán de Lober, Borge-Diez and Castro-Gil (2013) shows how, only by the optimisation of the system technique regulations, energy savings by a margin of 30% can be achieved in offices and administrative buildings. The functionality of the spaces was analysed in terms of accessibility and their suitability for users. An analysis of the available literature on the revitalisation of science facility spaces supported the ecological and functional assessment with results and studies from several international centres where university spaces have been adapted to meet new requirements. The study also included a comparative analysis that contrasted the implemented solutions with similar projects implemented on campuses in Poland and abroad. This made it possible to determine the effectiveness of the strategies applied in the context of international sustainability standards. The final assessment of the project was based on criteria such as the environmental sustainability of the solutions, the functionality of the space, the impact on the well-being of the users, and the involvement and satisfaction of the students resulting from their participation in the design process.

In terms of qualitative research, the data obtained from workshops and consultations were transcribed and subjected to a thematic coding process. Recurrent categories such as accessibility, comfort, and ecological awareness were identified, and representative quotations were used to support the design directions. Quantitative assessments included two main areas. First, biodiversity was evaluated through direct field observations and species richness counts carried out in designated vegetation patches, both before and after the design intervention. Second, potential energy savings were estimated by benchmarking the projected BMS performance against comparable cases reported in the literature, and by modelling operational scenarios based on building energy demand profiles. This mixed-methods protocol ensured that qualitative insights were systematically integrated with measurable environmental indicators, thus reinforcing reproducibility and transparency.

It is important to note that at the current conceptual stage, precise numerical values for anticipated savings and biodiversity increases could not be generated, as no operational monitoring data were available. Instead, the analysis relied on benchmarking against published case studies and design guidelines, which provide indicative ranges of performance for similar interventions.

RESULTS

Description of proposed landscaping

The landscaping strategy for the Water Centre redevelopment prioritises ecological resilience, climate adaptation, and user well-being through an integrated blue-green infrastructure approach. The design balances urban hardscape – a university plaza facilitating social interaction – with soft landscape zones,

including biodiverse green spaces and ecological corridors. Figure 1 illustrates the master plan, highlighting the integration of blue-green infrastructure with circulation routes. The placement of the infiltration troughs and the ribbon path demonstrates how ecological and social functions were combined in the design (Fig. 1).



1 – the Water Centre main building
2 – pavilion with a café and exhibition area
3 – Building 22 (Small Animals Clinic)
4 – Building 23 (Veterinary Medicine and Animal Science faculties' building)
5 – university square with coffee tables
6 – bike racks
7 – ribbon path
9 – quiet zone with benches
10 – green roof (sedum plants)
11 – infiltration ditch (bioswale)
12 – open rainwater channel
14 – microforest
15 – flower meadow
16 – parking area with permeable and green paving
17 – green glass/open-air cinema
18 – wild cherry
19 – new trees
20 – shrubs
21 – tall grass

Fig. 1. Master plan at the original scale of 1 : 500 showing a new complex vision of the Water Centre's surroundings incorporated into the existing campus tissue

Source: own work based on Google Maps (2025).

Key interventions include an autonomous rainwater circulation system consisting of retention basins, infiltration ditches, and an open rainwater channel. These features slow stormwater runoff, enhance water retention, and mitigate flooding risks (McNabb et al., 2024). Additionally, a hierarchical planting system – incorporating micro forests, flowering meadows, and native shrubs – enhances biodiversity while creating habitats for pollinators and small wildlife (Sutkowska et al., 2024).

A network of pedestrian and cycling routes connects the campus and reduces reliance on motorised transport, aligning with sustainable mobility principles (Działek, Jarecka-Bidzińska, Staniewska & Téoule, 2025). Integrating tree belts and vegetative buffers provides additional ecological benefits, such as reducing noise pollution and supporting carbon sequestration (Moscoso et al., 2024).

The project enhances environmental sustainability and social well-being by embedding NbS within the academic landscape, creating a climate-resilient and user-friendly university space.

One of the main pro-climate measures is a closed circulation of rainwater from the newly created university square, the pavilion's roof, and possibly from the green areas. The autonomous water system (with no connection to the sewerage system) contributes to slowing down surface runoff by collecting water while it is still on the roof. Any excess water flows via an open rain channel from the roof of the pavilion to an infiltration ditch (a depression of about 30 cm covered with grass or other vegetation that can withstand temporary flooding, flooded only in the event of excess rainwater). As shown in Figures 2 and 3, the design of infiltration ditches was inspired by precedents from Copenhagen, demonstrating how stormwater management features can double as landscape amenities. A large amount of greenery and the planting of shrubs, trees, tall grasses, and a flower meadow or green roof also contribute to improving the cooling function of the air, which positively affects human well-being during hot weather.



Fig. 2. An example of a rain garden/infiltration ditch from Copenhagen. An excess of stormwater from the roof is collected in a trough with grass vegetation

Source: photo by Barbara Warzecha 2024.



Fig. 3. An example of a rain garden/infiltration ditch from Copenhagen. A surface flow of stormwater can be collected in a trough with vegetation that withstands temporary flooding

Source: photo by Barbara Warzecha 2024.

A few pro-ecological measures have been proposed in the space between the existing and newly built structures. The designed forms of vegetation have been hierarchised into high vegetation (microforest), medium height vegetation (ornamental shrubs, grass garden), as well as low vegetation (green and permeable surface of the car park, green roof of the pavilion, flower meadow). Moreover, the species selection of shrubs allows for additional pro-ecological functions. Furthermore, the shrubs, which are attractive for their fruit, can serve as food for small animals during the winter. Animal sanctuaries with feeders and wintering areas (e.g. for hedgehogs) have been created in the microforest. Shrub belts have been located along urban axes, their species selection allowing them to be left to grow freely or trimmed if they are located next to traffic routes, as necessitated by considerations of safe pedestrian movement. A refuge for insects could become the proposed flower meadow, situated along the ribbon path, away from the main traffic arteries. The microforest acts as an ecological route or space and wraps around the campus site along its boundaries, creating an acoustic barrier from adjacent busy roads.

Mitigation measures for climate change could start here by promoting low-impact pedestrian and cycle transport on campus, improving pedestrian safety (lanes, new pavements, new paths), implementing green paving, and planting trees in the existing car park at the south entrance of the campus.

Architectural interventions

The design for the redevelopment of the existing Water Centre building, together with the development, considers the versatility of solutions, improved acoustics, environmental friendliness, and energy efficiency. Currently, the complex comprises the water park, which is left unchanged, an undeveloped green area, and the university building. The building area is 1,850 m^2, and the total floor area is 5,000 m^2. The building has a teaching, representative, and conference function.

The redevelopment includes extending ancillary functions, constructing a pavilion with an exhibition and educational function, and developing a green area, along with a green terrace. The terrace will be an experimental opportunity for students to design and maintain marsh gardens. The greenery has been tidied up and enhanced with seating areas created along the landscape ‘ribbon’ leading to the pavilion and building. Along the ribbon path will be places for tranquillity, dining, or contact with nature. The traffic network is divided into transit routes and walking paths. Main arteries and side axes provide communication between the campus buildings. New connections have been introduced in place of ‘forecourts’. The redesign of pavements has improved pedestrian comfort and safety. The newly designed plaza between the Water Centre and the pavilion creates an intimate atmosphere and encourages people to meet and linger among the greenery, including in the proposed café. To the pavilion’s rear, additional usable space has been created by moving the fence and gate 20 m into the area around the Water Centre, thus creating a forecourt and meeting place around the pavilion building. Here, in a secluded location, it is also possible to hold outdoor activities or a summer cinema screening, with the back wall of the pavilion acting as a screen.

As a result of pre-design analyses, it was determined that the Water Centre building required an increase in the number of teaching rooms and the planning of an attractive central space, as well as the separation of the conference space to allow independent use of the building. Figure 4 visualises the division into transformation zones, distinguishing between areas of preservation (grey), internal reconstruction (yellow), and structural extension (blue). This diagram clarifies the phased approach adopted to ensure continuity of the Water Centre’s operation during redevelopment. Three transformation zones were planned for the facility: extensions and alterations. Due to the need for the facility to function, the zones have been divided into a no-change zone (grey), where activities can occur almost without interference during construction. A new part (yellow), a conversion zone without interference with the building structure, and a new building extension zone (blue). The projected extent of the changes is shown in Figure 4.

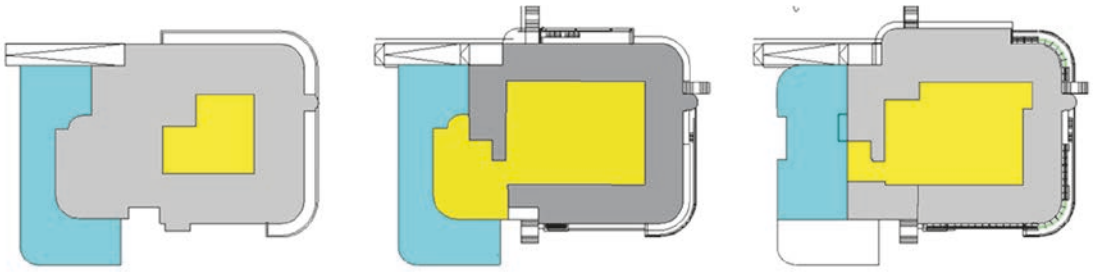


Fig. 4. Diagram of the planned changes to the building depending on the degree of transformation: grey – no change, yellow – reconstruction without interfering with the building structure, blue – extension, interfering with the structure (left: basement, middle: ground floor, right: 1st floor)

Source: own work.

The central space of the building was redesigned to encourage student use. The design includes the replacement of a disused fountain with a multi-purpose grandstand-style staircase acting as an amphitheatre. Among other things, a projection installation has been planned that, together with a skylight shading system and mobile acoustic walls, will allow lectures to take place. The grandstand will be made of wood to make the interior warmer. Under the grandstand, the so-called 'Atelier' has been designed as an exhibition and workshop space for architecture students, fenced off with transparent glass so that the observer can watch the exhibition from outside without disturbing the work inside.

In the common spaces, small-group workspaces have been provided, adapted to the needs of people with visual, hearing, or mobility disabilities. Quiet workspaces, so-called 'learning boxes', have also been designed, which lecturers and students can use to conduct and participate in remote classes.

Currently, the building has two large halls, one small conference and lecture room, specialist labs, and computer labs. The expansion project envisages the addition of three new large lecture/conference rooms and a multi-purpose room that can be divided into smaller practice rooms as required. A mobile wall system has been proposed for the division, which, when folded, will allow the space to be used as a banquet hall. An additional advantage is the proximity of the café and catering facilities.

A café has been designed on the south side of the building, accessible from the car park. The connection between inside and outside will be achieved through a high glass façade topped by a 'green wall'. This provides an independent entrance for conferences held in the new part of the building without interfering with the activity and accessibility of the existing part of the building.

Sustainable solutions

The ventilation and air-conditioning units in the building are intended to provide hygienically adequate fresh air, extract stale air, and maintain the required indoor air parameters for the individual areas. Heat gains in the rooms will be discharged via a cooled ventilation air supply and water underfloor cooling, while the heat demand will be covered by water underfloor heating. All rooms will be provided with mechanical, supply, and exhaust ventilation. Climatic conditions for individual rooms will be determined based on future data from the investor regarding the temperature and humidity levels that should be maintained, as well as the requirements for individual laboratory rooms, applicable regulations, and technological guidelines. The heat source for the building will be a ground heat exchanger in the form of vertical boreholes. Heat pumps will modify the ground heat exchanger facility's medium parameters. In addition, one heat pump will have the capacity to produce hot water and water for cooling purposes. To ensure the uninterrupted operation

of the heat pumps as a cooling source, a fan cooler on the building's roof is envisaged. Underfloor heating is envisaged in the open-plan areas; the laboratory and office spaces will have panel radiators.

Cost-reducing solutions

The leading solutions to reduce running costs are energy recovery as much as possible and the use of grey water, as described in detail in the section on pro-environmental solutions. Another solution to reduce running costs is the double curtain wall or double-skin façade in the extension. The space between the two planes of the curtain wall is approximately 60 cm and provides a buffer of air that is insulated in the space between, allowing the rooms it encloses to remain passively warm. In addition, it reduces and eliminates the load caused by solar energy (excessive heating of the façade). In the newly designed south façade, an entirely glazed, double-layered partition and expandable horizontal wooden blinds are designed to support shading as required. In addition, in line with the façade design, vertical panels have been used to reduce light access to the classrooms and save on air conditioning. Meanwhile, photovoltaic glass was proposed in the outer layer of the façade, supporting the extraction of electricity from traditional photovoltaic cells on the roof.

In addition, motion-responsive adaptive lighting will be used around the building to reduce energy consumption significantly (principle of reduction), turning on light only where needed. The biowaste created will be recycled into fertiliser, supporting the maintenance of the greenery around the building and being in line with the idea of recycling (principle of recycling). In addition, materials from the current building, such as bricks, steel, and glass, will be reused in the new design, which fits in with the principle of reuse and minimises the need for new raw materials.

Area versatility

The facility will be fully adapted to the needs of people with disabilities, considering various forms of support and mobility solutions for people with reduced mobility, such as ramps, lifts, and signage at eye level for wheelchair users. There will also be several facilities for the deaf, hard of hearing, blind, and visually impaired. The building will be equipped with systems that work with users' smartphones, enabling them to navigate and use the space in their preferred way. For example, blind and visually impaired people can use a dedicated app that provides voice guidance to help them navigate the facility.

Acoustics

As part of the use of modern materials in the public area, a development has been proposed to form a grandstand-style staircase. Wood has been used as an acoustically insulating material to soundproof this space, reinforced with corrugations to allow early sound reflections to achieve good acoustics. In addition, soundproofing elements in the form of mobile panels and sound-absorbing materials capable of adapting to functional needs have been proposed. A membrane will be spread over the seats, which, together with their wooden finish, will improve the acoustic performance. The design incorporates the use of wooden movable screens, allowing the space to be visually closed off to the presenter.

Pro-environmental solutions

The project uses environmentally friendly solutions inside and outside the building: architecture, landscaping, and ecosystem services. An off-grid (grid-independent) photovoltaic installation was designed, and surplus energy will be stored in batteries for use during reduced production. The stored energy will be used partly for heating and cooling the central heating and water system. Rainwater from the roof will be retained and used for utility purposes, thereby reducing water demand. A room is foreseen on floor −1 for filtering and pumping water to reuse points such as flush toilets, urinals, and outdoor green watering boxes. Surface rainwater from the square and excess water from the green roof are routed through an open rainwater channel

with the overwater greenery or through underground pipes to a rainwater basin/garden with vegetation that temporarily tolerates flooding. This self-contained system does not require a connection to the sewer system, and the water is managed in situ.

DISCUSSION

The design outcomes presented in the 'Results' section exemplify how ecological and architectural interventions can be mutually reinforcing. For example, the master plan (Fig. 1) demonstrates integration of blue-green systems with mobility infrastructure, while the building transformation strategy (Fig. 4) shows how functional adaptability was embedded into the architectural fabric. These solutions align with broader frameworks such as the European Green Deal and biophilic design principles, reinforcing the conceptual contribution of the project.

The Water Centre is a specialised building with modern laboratory and field research equipment. It is the only research facility in Poland dedicated to water science. There are laboratories to study the processes that determine water flow under various conditions. Spatial analysis is carried out in computer labs. At the same time, the Water Centre's external garden in the same urban complex includes experimental models of the river, spring, pond, and numerous water structures, as well as a meteorological station measuring current weather conditions.

The construction project was designed in 2005. It is a relatively new building with existing executive documentation. Since then, the following 20 years have been critical in the Polish construction industry due to Poland's accession to the European Union and the consequent entry into force of regulations on sustainable development in the construction industry. Today, two decades later, sustainable development in the construction industry is not just a trend but a conscious design covered by regulation. Directive (EU) 2024/1275 increased the energy performance requirements for new buildings.

It requires all new residential and non-residential buildings to be zero-carbon buildings as of 1 January 2028, as well as for buildings owned by public authorities, and, as of 1 January 2030, for all other new buildings.

The guidelines for the competition project, which included upgrading the Water Centre, addressed the following categories: circular economy, space and function adaptation, energy, greenery with surrounding infrastructure, and site development. The project team's analysis showed the need for changes in all these categories, resulting in the conceptual design of the Water Centre and its surroundings. While the conceptual design allows for the identification of expected benefits, detailed quantitative validation (e.g. measured reductions in energy use, stormwater runoff, or species inventories) will only be possible after implementation. Future monitoring is therefore essential to verify the projected performance and to provide empirical evidence supporting the sustainability claims.

For the conceptual design created based on the competition for the redevelopment of the Water Centre to develop further, it is necessary to carry out a series of analyses and expert opinions that are the starting point for further design work (construction-tender design).

In the case of the circular economy, the analyses and expert opinions should concern the types and quantities of building materials that can be reused, the possibility of storing them during construction (inventory with a list of how many times the material has been used), and the demonstration of appropriate technical parameters to meet construction standards when re-built so that the building can be handed over for use according to Polish construction regulations.

In the case of space and function adaptation, a detailed analysis of the needs of the Warsaw University of Life Sciences – SGGW campus in terms of teaching, auditorium, and laboratory spaces for the next 10–20 years should be carried out, considering the university's development plans. In addition, these analyses

should consider the plan for possible phasing of the works to allow the use of the building during construction, renovation, and adaptation works.

As for the design of installations (sewage, water, heating, ventilation, and fire protection), providing, among other things, energy in the designed building should be carefully inventoried and analysed for capacity and possible expansion to meet nearly zero-energy building requirements.

The Directive (EU) 2024/1275 leads member states toward achieving 'nearly zero-energy buildings', which can be described as those with very high energy performance. Buildings like those described need two parameters: minimal energy to operate, and energy sourced from renewable resources generated locally (Starzyk et al., 2024).

Greenery and the surrounding infrastructure and utilities should be carefully analysed and designed according to the reports and EU regulations. The urban layout, which requires thorough sunlight and acoustic analysis around the building, will remain important. The external area of the Water Centre should be integrated with the building and function as one entirely complementary organism.

Solutions importance

The pro-environmental solutions used in the Water Centre expansion project are key to reducing the building's operating costs and improving the quality of life for its users. Integrating energy-saving technologies, such as photovoltaic installations and rainwater retention systems, contributes to a significant reduction in energy and water consumption, directly impacting the facility's operating costs. The introduction of an energy storage system from photovoltaic panels and the use of rainwater for irrigating greenery and flushing toilets exemplify the use of modern technologies to support resource management (Pronk et al., 2021; Dzikuć, Piwowar & Dzikuć, 2022). This approach minimises the load on the urban infrastructure while contributing to the energy self-sufficiency of the campus.

One of the key environmental solutions is using green roofs and rain gardens, which have multidimensional ecological and social functions. In addition to reducing the urban heat island effect, green roofs and other greenery support local biodiversity, improve air quality and provide better microclimatic conditions (Zhong, Schroeder & Bekkering, 2023). For campus users, these benefits translate into increased thermal comfort, reduced noise levels and aesthetic qualities of the environment. As a result, the space becomes more user-friendly, positively impacting users' daily well-being and productivity.

Another innovative design element is using a double-skin façade on the building, which acts as a thermal buffer. The double-skin façade reduces heat loss in the winter months while reducing overheating in the summer (Roostaei Firouzabad & Razi Astaraei, 2024). This passive solution reduces the need for mechanical heating and cooling systems, reducing operating costs and greenhouse gas emissions. In addition, adaptive motion-responsive lighting enhances energy efficiency (Oh & Lim, 2025). The use of recycled materials is in line with the concept of a closed-loop economy, reducing the consumption of raw materials and the generation of waste (Łacek & Starzyk, 2023).

However, the solutions go beyond purely economic aspects. Promoting ecology in an academic environment has essential educational and cultural significance. Elements of blue-green infrastructure, such as rain gardens and microforests, not only improve the quality of life for users but also become spaces for learning and observing ecological processes occurring in urban fauna and flora (Sutkowska, Stefańska, Vaverkova & Matsui, 2024). Such initiatives inspire the academic community to implement similar practices in other areas of life while promoting environmental awareness and responsibility. These elements align with contemporary sustainability frameworks, such as the European Green Deal (European Commission [EC], 2021), and climate adaptation strategies recommended by the Intergovernmental Panel on Climate Change (IPCC, 2023).

CONCLUSIONS

Key lessons for sustainable campus design

The sustainable design of university campuses plays a key role in shaping spaces that minimise negative environmental impacts and enhance the university community's quality of life. The analysis of the Water Centre extension allows for some fundamental conclusions regarding the design of ecological and participatory university spaces.

Integrating blue-green infrastructure as a standard design element is one of the most relevant aspects. Contemporary campuses should use rainwater retention systems, green roofs, rain gardens, and microhabitats to increase biodiversity. Such solutions not only reduce the environmental footprint but also improve the microclimate and the overall comfort of the space. In the case of the Water Centre, rainwater retention and infiltration systems have significantly reduced urban water consumption and increased the site's resilience to extreme weather conditions.

Energy efficiency and the move towards energy self-sufficiency for campuses are also essential elements of sustainable design. The use of low-carbon technologies, such as photovoltaic panels, intelligent energy management systems (BMS), or double-skin façades, allows for a significant reduction in energy consumption, which has a direct impact on reducing operating costs and carbon emissions. In the case of the project in question, implementing these solutions has shown that modern campuses can effectively strive for climate neutrality, which fits with global sustainability goals.

Another critical issue is users' participation - especially students - in the campus design process. Involving the academic community in consultations and design workshops enables spaces to better adapt to users' actual needs, increasing their involvement in the university's life and their sense of responsibility for the shared space. In the Water Centre project, the participatory approach has made it possible to create spaces that better respond to the needs of both students and academic staff.

From a utilitarian perspective, the multifunctionality and flexibility of campus spaces are also extremely important. Today's universities should offer spaces that can be adapted for different activities – teaching, research, and leisure. Modern spaces, such as mobile conference rooms, open amphitheatres or relaxation zones, enable better use of infrastructure and support interdisciplinary interactions. The example of the Water Centre shows that this approach improves the quality of academic spaces, making them more dynamic and open to the changing needs of users.

Campus inclusivity and accessibility cannot be overlooked either. They should be designed with all users in mind, regardless of their physical or sensory abilities. Innovative navigation systems, architectural amenities, and ergonomic working and resting spaces help create an inclusive environment that allows people with different needs to use academic spaces freely.

A final key issue remains the long-term monitoring of the upgrades' impact. Implementing modern technologies and green solutions requires their systematic evaluation, which allows ongoing optimisation and adaptation of projects to new challenges. Implementing space use analysis systems is recommended, allowing the effectiveness of the applied strategies and their impact on academic life to be effectively assessed.

Recommendations for designers and academic institutions

Based on the Water Centre expansion project analysis and its impact on the campus space's functionality, environmental performance and quality, several recommendations can be made for designers and academic institutions planning to upgrade university infrastructure.

The first key recommendation is to incorporate sustainability principles as a central element of the design process. Solutions such as green roofs, rainwater retention systems, or the integration of renewable energy sources should be standard in the design of modern campus buildings. Such technologies not only

contribute to lower operating costs but also have a positive impact on the environment and the quality of life of the occupants. It is vital that designers carefully analyse local environmental and social conditions, adapting solutions to the site's specifics.

A second important recommendation is to promote users' participation – especially students – in the design process of campus spaces. Workshops and consultations can provide valuable information about their needs and expectations, allowing the design to be better adapted to the actual requirements of the academic community. Users' participation in the decision-making process also increases their involvement and ownership of the use of the space. Another important aspect is to ensure the inclusivity of the designed spaces. Accessibility for people with different types of disabilities, considering both architectural and digital solutions, should be one of the priorities. Designing inclusive spaces for all user groups fosters a more open and supportive academic environment. It is also recommended that more attention be paid to the quality of communal spaces. These should be conducive to both focused work and social integration. Introducing solutions such as learning box spaces, relaxation areas or multifunctional rooms that can be adapted to different needs increases the functionality of the campus and supports academic activity. Academic institutions should conduct regular analyses of the effectiveness of the technologies used, their level of use, and user satisfaction. Such data can provide a valuable knowledge base to support subsequent modernisation projects.

Proposal for in-depth studies

The Water Centre expansion project opens up a wide range of opportunities for further research into the impact of upgrading university infrastructure on academic life and the realisation of sustainability. As such, several key areas are proposed for further analysis.

The first relevant direction is the long-term evaluation of the impact of the architectural and environmental solutions applied to the daily functioning of the academic community. This research could include an analysis of changes in how students and staff use spaces, an assessment of their satisfaction with the facilities introduced, and the impact of these changes on social integration, psychological well-being, and learning efficiency. It would be exciting to track how modern communal spaces – such as the indoor amphitheatre or individual work zones – affect how users interact and engage in academic life.

A second area of research could be analysing the effectiveness of environmental solutions and their impact on the environment. For example, it is worth investigating how green roofs, rain gardens, and other plantings contribute to improving air quality and rainwater retention or reducing the urban heat island effect. Long-term monitoring of these processes will make it possible to assess the implemented technologies' effectiveness and adaptability to changing climatic conditions.

Another potential research direction is economic analysis, which would assess the impact of the applied technologies on reducing building operating costs. It would be worth tracking the extent to which photovoltaic panels, BMS, or the use of recycled water translate into reduced resource consumption and maintenance expenses. Such a study could also include a comparative analysis with other university buildings with similar solutions.

The impact of a participatory approach on the perception of campus spaces by the university community may also be an interesting issue. The influence of student participation in the design process on their subsequent involvement in university life, sense of belonging, and satisfaction with the designed spaces can be explored.

Ultimately, exploring how campus spaces can be used for innovative research and teaching projects is also proposed. Spaces such as green zones, laboratories or technological installations (e.g. photovoltaics) can become the base for interdisciplinary research projects and practical activities that bring together students and staff from different departments.

In summary, future research into the modernisation of university campuses should include social, ecological, and economic aspects. Long-term monitoring and analysis of implemented solutions will enable

the development of knowledge on the sustainable design of academic spaces and contribute to the improvement of future projects of this type.

Study limitations

The analysis provided important insights into the modernisation of campus facilities. However, the study focuses on selected cases, which do not exhaust the entire spectrum of possible approaches to redeveloping academic buildings. The availability of data on the effectiveness of the implemented solutions is limited, especially regarding the long-term operation of the buildings after modernisation. In addition, the analysis does not comprehensively consider economic and political factors that may influence university investment decisions. Another challenge is the lack of long-term user research on their perception of changes to the academic space. Future research should be deepened with an analysis of the long-term effects of retrofitting, including an assessment of user comfort, energy efficiency, and operating costs in the broader context of the operation of university campuses.

The absence of detailed operational data and long-term monitoring directly affects the validity of the presented results. As the study is based on conceptual design and comparative analyses, the findings should be understood as indicative projections rather than definitive evidence of sustainability performance. This limitation means that claims about energy savings, water management efficiency, or biodiversity enhancement cannot yet be empirically verified. Consequently, while the proposed strategies are consistent with best practices and supported by literature benchmarks, their actual effectiveness will depend on future implementation and systematic evaluation.

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Authors' contributions

Conceptualisation: A.S.; methodology: A.S.; validation: K.W. and M.K.; formal analysis: M.K. and M.S.; investigation: M.S. and M.K.; resources: P.N.; data curation: M.S.; writing – original draft preparation: A.S., K.W., M.K., M.S., and B.W.; writing – review and editing: A.S. and K.W.; visualisation: B.W., M.S. and J.K., supervision: A.S.; project administration: A.S.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Colmenar-Santos, A., Terán de Lober, L. N., Borge-Diez, D. & Castro-Gil, M. (2013). Solutions to reduce energy consumption in the management of large buildings. *Energy and Buildings*, *56*, 66–77. https://doi.org/10.1016/j.enbuild.2012.10.004

Directive (EU) 2024/1275 of the European Parliament and of the Council of 24 April 2024 on the energy performance of buildings (recast) (Text with EEA relevance) (PE/102/2023/REV/1). OJ L, 2024/1275, 8.5.2024.

Działek, J., Jarecka-Bidzińska, E., Staniewska, A. & Téoule, F. (2025). (Re)greening transition of academic green spaces as a response to social and environmental challenges: the role of bottom-up initiatives. *Urban Forestry & Urban Greening*, 128692. https://doi.org/10.1016/j.ufug.2025.128692

Dzikuć, M., Piwowar, A. & Dzikuć, M. (2022). The importance and potential of photovoltaics in the context of low-carbon development in Poland. *Energy Storage and Saving*, *1* (3), 162–165. https://doi.org/10.1016/j.enss.2022.07.001

European Commission [EC] (2021). *Delivering the European Green Deal*. Retrieved from: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en

Ibiyeye, A. I., Shamang, K. J. & Malachy, G. (2024). Awareness of building sustainability: A case of architectural students of Kaduna state university. *Social Sciences & Humanities Open*, *10*, 100927. https://doi.org/10.1016/j.ssaho.2024.100927

Intergovernmental Panel on Climate Change [IPCC] (2023). *AR6 Synthesis Report Climate Change*. https://www.ipcc.ch/report/ar6/syr/

Jakimiuk, A., Matsui, Y., Podlasek, A., Koda, E., Goli, V. S. N. S., Voběrková, S., Singh, D. N. & Vaverková, M. D. (2023). Closing the loop: A case study on pathways for promoting sustainable waste management on university campuses. *Science of The Total Environment*, *892*, 164349. https://doi.org/10.1016/j.scitotenv.2023.164349

Kamali, S., Khakzar, G. & Abdali Hajiabadi, S. (2013). Effect of Building Management System on Energy Saving. *Advanced Materials Research*, *856*, 333–337. https://doi.org/10.4028/www.scientific.net/AMR.856.333

Kulpa-Puczyńska, A. (2022). University spaces for cooperation strengthening pro-innovative attitudes of academic community. *Forum Pedagogiczne*, *11* (2), 285–295. https://doi.org/10.21697/fp.2021.2.21

Łacek, P. & Starzyk, A. (2023). Recycling of building materials: an overview. *Acta Scientiarum Polonorum. Architectura*, *21* (3). https://doi.org/10.22630/ASPA.2022.21.3.23

McNabb, T., Charters, F., Dionisio, R., Challies, E. (2024). Design and implementation of blue-green infrastructure for socio-cultural benefits at community scales: The case of Wigram Basin in Ōtautahi Christchurch. *Nature-Based Solutions*, *6*, 100192. https://doi.org/10.1016/j.nbsj.2024.100192

Moscoso, C., Morad, R., Oksvold, A., Dimmen, O., Skjermo, J. & Tangrand, K. (2024). Increasing citizen engagement in sustainable architecture using augmented reality: A pilot study. *Computers in Human Behavior Reports*, *16*, 100498. https://doi.org/10.1016/j.chbr.2024.100498

Oh, S-T. & Lim, J-H. (2025). Natural light adaptive context lighting system that provides a lighting environment tailored to the User's objectives. *Heliyon*, *11* (2), e42064. https://doi.org/10.1016/j.heliyon.2025.e42064

Pronk, G. J., Stofberg, S. F., Van Dooren, T. C. G. W., Dingemans, M. M. L., Frijns, J., Koeman-Stein, N. E., Smeets, P. W. M. H. & Bartholomeus, R. P. (2021). Increasing Water System Robustness in the Netherlands: Potential of Cross-Sectoral Water Reuse. *Water Resources Management*, *35* (11), 3721–3735. https://doi.org/10.1007/s11269-021-02912-5

Roostaei Firouzabad, M. & Razi Astaraei, F. (2024). Energetical effect of electrochromic glazing on the double-skin façade of the building in different climates. *Energy and Buildings*, *316*, 114344. https://doi.org/10.1016/j.enbuild.2024.114344

Starzyk, A., Rybak-Niedziółka, K., Nowysz, A., Marchwiński, J., Kozarzewska, A., Koszewska, J., Piętocha, A., Vietrova, P., Łacek, P., Donderewicz, M., Langie, K., Walasek, K., Zawada, K., Voronkova, I., Francke, B. & Podlasek, A. (2024). New Zero-Carbon Wooden Building Concepts: A Review of Selected Criteria. *Energies*, *17* (17), 4502. https://doi.org/10.3390/en17174502

Stefańska, A., Chudzińska, A., Kurcjusz, M., Sutkowska, M., Krawczyk, J. & Dixit, S. (2023). Urban Energy Recycling: An Architectural Road Map. *Proceedings of the Creative Construction Conference 2023*, 645–649. https://doi.org/10.3311/CCC2023-083

Sutkowska, M., Stefańska, A., Vaverkova, M. D. & Matsui, Y. (2024). Fostering sustainable Urban Development: Integrating School Areas for supporting the City's Blue-Green Infrastructure. *Acta Scientiarum Polonorum. Architectura*, *23*, 12–31. https://doi.org/10.22630/ASPA.2024.23.2

Vaverková, M. D., Polak, J., Kurcjusz, M., Jena, M. K., Murali, A. P., Nair, S. S., Aktaş, H., Hadinata, M. E., Ghezelayagh, P., Andik, S. D. S., Rahmana, A. & Franc-Dąbrowska, J. (2024). Enhancing Sustainable Development Through Interdisciplinary Collaboration: Insights from Diverse Fields. *Sustainable Development*, *33*, 3427–3454. https://doi.org/10.1002/sd.3302

Wichowski, P., Rutkowska, G., Kamiński, N. & Trach, Y. (2019). Analysis of Water Consumption in the Campus of Warsaw University of Life Sciences – SGGW in Years 2012–2016. *Journal of Ecological Engineering*, *20* (5), 193–202. https://doi.org/10.12911/22998993/105473

Zagrajek, K., Kłos, M., Rasolomampionona, D. D., Lewandowski, M., Pawlak, K., Baran, Ł., Barcz, T., Kołaczyński, P. & Suchecki, W. (2023). Investing in Distributed Generation Technologies at Polish University Campuses during the Energy Transition Era. *Energies*, *16* (12), 4575. https://doi.org/10.3390/en16124575

Zhong, W., Schröder, T. & Bekkering, J. (2022). Biophilic design in architecture and its contributions to health, well-being, and sustainability: A critical review. *Frontiers of Architectural Research*, *11* (1), 114–141. https://doi.org/10.1016/j.foar.2021.07.006

Zhong, W., Schroeder, T. & Bekkering, J. (2023). Designing with nature: Advancing three-dimensional green spaces in architecture through frameworks for biophilic design and sustainability. *Frontiers of Architectural Research*, *12* (4), 732–753. https://doi.org/10.1016/j.foar.2023.03.001

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STRESZCZENIE

Artykuł analizuje rolę projektowania zrównoważonego i partycypacyjnego w modernizacji kampusu na przykładzie rozbudowy Centrum Wodnego SGGW. Badanie obejmuje integrację proekologicznych strategii, takich jak: zielone dachy, recyrkulacja wody deszczowej, systemy energii odnawialnej oraz zaangażowanie studentów w planowanie przestrzenne. Wykorzystując podejście studium przypadku, oceniono wpływ tych interwencji na funkcjonalność kampusu, dobrostan użytkowników oraz odporność środowiskową. Wyniki wskazują, że modernizacja zrównoważona kampusów nie tylko poprawia warunki mikroklimatyczne i bioróżnorodność, lecz także sprzyja inkluzywności i zaangażowaniu społeczności akademickiej. Artykuł wnosi wkład w dyskusję na temat urbanistyki ekologicznej oraz adaptacji przestrzeni akademickich do współczesnych wyzwań rozwoju zrównoważonego.

Słowa kluczowe: projektowanie zrównoważone, infrastruktura kampusu, niebiesko-zielona infrastruktura, architektura uniwersytetu

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CAN AN ARCHITECT'S DREAMS BECOME REALITY? A CASE STUDY OF PERFUMIARNIA IN POZNAŃ

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ABSTRACT

The paper presents a case study of the Perfumiarnia residential development in Poznań, demonstrating how an architectural vision was translated into spatial and technological solutions within the historical and natural context of the Łazarz district and Wilson Park. The methods include historical and urban context analysis, design analysis, and interpretation of changes during implementation. The findings indicate that architectural quality arises from a deep reading of the site, integration with greenery, and careful material and detail decisions, while maintaining urban coherence despite market pressures. In response to COVID-19 and rising costs, design adjustments were introduced without abandoning the core concept, emphasising flexibility, negotiation, and stakeholder cooperation. Perfumiarnia in Poznań is proof that architectural "dreams" can be realised when grounded in context analysis, pragmatism, and sensitivity to social and economic conditions.

Keywords: residential architecture, case study, context, Wilson Park, flexibility, urban regeneration

INTRODUCTION

Architecture operates at the boundary between imagination and real-world constraints. Every undertaking requires translating a concept into solutions that can be built, while maintaining a dialogue with urban, social and natural contexts. This paper presents the design and implementation process of Perfumiarnia (Fig. 1) in Poznań – located on the former perfume factory site, directly adjacent to Wilson Park – and addresses how an initial vision can be confronted with economic and technical realities, then preserved in its key assumptions through delivery.



Fig. 1. Architectural model

Source: JEMS Architekci.

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MATERIAL AND METHODS (AIM AND HYPOTHESIS)

A case study approach was adopted (Yin, 2015), comprising:
– Analysis of the historical context (the evolution of the Łazarz district).
– Urban analysis (relationships with Wilson Park and the surrounding urban fabric).
– Design analysis (creative process and adopted spatial/material solutions).
– Interpretation of changes during implementation (market conditions, COVID-19 pandemic, costs).

The author's aim in the paper was to examine how the architect's vision can be realised in practice and what factors facilitate or hinder this process.

To achieve the intended goal, the author formulated the following research hypothesis: The vision can be realised if it is supported by an in-depth contextual analysis – including a reading and reinterpretation of the *genius loci* – and paired with openness to design compromises enabling adaptation to changing delivery conditions.

Historical and urban analysis

Historical context

Łazarz is one of Poznań's districts of particular cultural and urban significance. Its development dates to the late 19th and early 20th centuries, when modern urban planning principles were strongly emphasised. Major influence is attributed to Joseph Stübben, whose concepts highlighted public greenery, view axes and representative squares (Kodym-Kozaczko, 2007). Within this paradigm, Wilson Park was also developed, and it remains a key recreational space to this day. The park's origins go back to 1834; in 1902, the area was opened to the public as the city's first botanical garden, with the official opening in 1903. Hermann Kube shaped a layout combining a French-style formal garden and an English picturesque landscape, with a palm house, a bandstand and a system of ponds and islands (Poznańskie Klimaty, 2020; Palmiarnia Poznańska, 2021; Fig. 2).



Fig. 2. Wilson Park, southern landscape section

Source: Jan Damięcki.

Significance of the location

The former perfume factory site – immediately adjacent to Wilson Park – required careful reconciliation of historical and natural values with the needs of contemporary housing. The new intervention had to embed itself in the site's narrative: sustaining memory while adding a new quality.

Urban determinants

Development in this part of Łazarz district was linked to plans for structuring perimeter blocks (e.g. along Matejki street). The prevailing typology is compact, street-front (pavilion-free) perimeter blocks opening their interiors to green courtyards (Fig. 3). Śniadeckich street introduced, for its time, innovative front courts and gardens that improved daylighting and ventilation (Fig. 4). The district's character is further shaped by vertical façade compositions, bays, oriels, and deep window reveals (Kodym-Kozaczko, 2007).



Fig. 3. Site plan

Source: JEMS Architekci.



Fig. 4. Tenement house on Śniadeckich street

Source: Jan Damięcki.

Historical and urban analysis summary

As a result of the urban analysis, key design constraints were identified:

– Immediate proximity to Wilson Park – necessitating openness to greenery and preservation of view corridors.
– Diverse age and quality of the surrounding urban fabric – calling for a formally restrained but high-quality response in detail.
– Identity of the site – symbolically recalling the factory's history in the new intervention.

In conclusion, the historical-urban background served as the starting point for a contemporary residential ensemble deeply rooted in the site's material and immaterial context.

RESULTS – DESIGN SOLUTIONS

Implications of location and context

The adjacency of Wilson Park and the high-quality inner-city urban fabric determined: a six-volume composition, a two-zone layout (entrance zone to the east / garden zone to the west), maximum opening of dwellings to greenery, and a pedestrian-first sequence of passages.

Form and massing

The ensemble was conceived as a modern, restrained composition articulated by vertical rhythms. Six visually distinct volumes were organised into three pairs (Fig. 5).



Fig. 5. Master plan

Source: JEMS Architekci.

Building height and scale harmonise with the surroundings – avoiding dominance over the park and historic tenements. "Urban canyons" in the entrance zone structure movement towards the garden; vertical façade setbacks enhance daylight and recall the tectonics of early 20th-century tenements.

Relationship with greenery

A key leitmotif is immersing architecture in greenery (Fig. 6): large windows, terraces, and balconies open towards the park; climbers and a planting gradient create a seamless transition from formal to garden spaces. Greenery permeates lobbies, the fissures between volumes and the roofs (layered green-roof build-ups).



Fig. 6. Aerial 3D view (from the south-west)

Source: JEMS Architekci.

Materials and details

Façades are finished with refined plasters, giving the ensemble a timeless character. Concave elevations are complemented by perforated stainless-steel fabric screens (Fig. 7), which run on steel brackets with concealed trolleys. The solution marries aesthetics and function, forming an "elastic boundary" for privacy and solar control – in the sense discussed in the paper by Alexander, Ishikawa and Silverstein (2008).

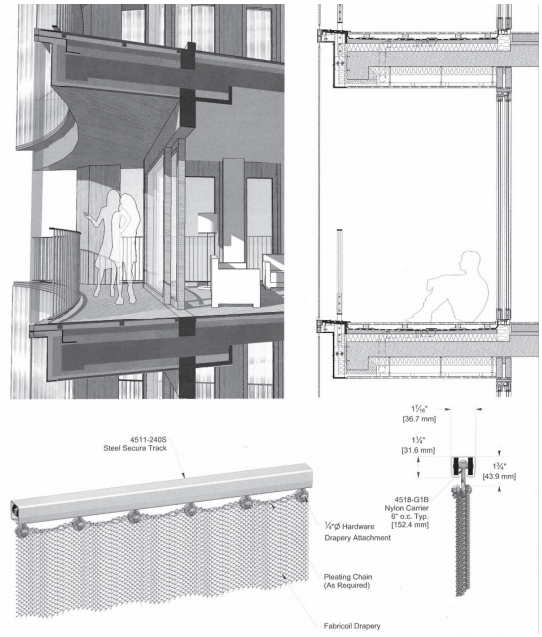


Fig. 7. Curved terrace details

Source: JEMS Architekci.

Functionality and internal layout

The ground floor plan (Fig. 8) provides recessed entrances with bicycle/buggy rooms, service uses to the east, and private terraces to the west.



Fig. 8. Ground floor plan

Source: JEMS Architekci.

The sections are served by central circulation cores (staircase and lift), enabling efficient dual-aspect daylighting (Figs 9–10).



Fig. 9. Typical floor plan

Source: JEMS Architekci.

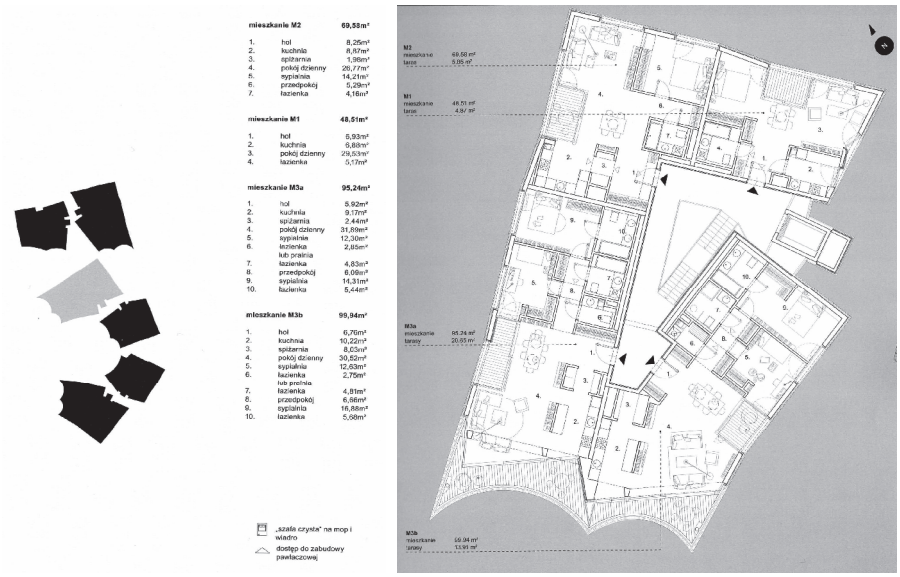


Fig. 10. Typical floor plan – Segment C

Source: JEMS Architekci.

The site's natural fall (approx. 1 m) enriches the composition. In larger dwellings, two opposite terraces increase façade transparency: subtly curved balconies and loggias frame views of the park (Fig. 11).



Fig. 11. Interior view towards Wilson Park

Source: Jan Damięcki.



Fig. 12. Master plan

Source: JEMS Architekci.

Implementation process and challenges

Supply-chain disruptions and cost increases during the COVID-19 period necessitated modifications: pairing segments and introducing single-storey connector pavilions, along with simplifying selected technologies (Figs 12–17). Core aesthetic, spatial and functional assumptions were retained; compositional coherence was maintained through a consistent order of volumes and details. The market context for these decisions is reflected in construction-cost and housing-market indicators (Główny Urząd Statystyczny [GUS], 2022; Narodowy Bank Polski [NBP], 2023).



Fig. 13. Ground floor plan

Source: JEMS Architekci.



Fig. 14. Typical floor plan

Source: JEMS Architekci.

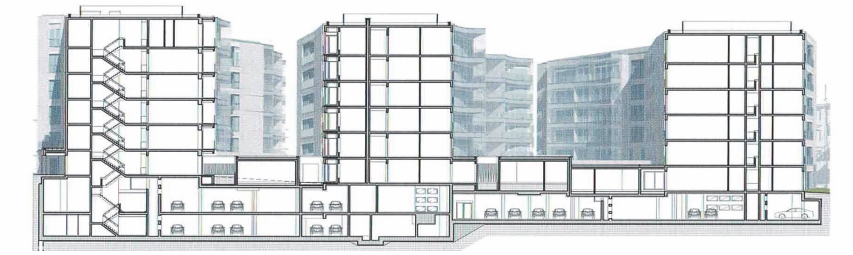


Fig. 15. Section A–A

Source: JEMS Architekci.



Fig. 16. View from Wilson Park

Source: Maria Kot.



Fig. 17. Close-up view from Wilson Park

Source: Maria Kot.

Design analysis summary

As a result of the analysis of the adopted spatial and material solutions, key characteristics of the design were determined:

– Modernity in dialogue with tradition and landscape.
– Multi-layered integration of greenery.
– Detail and materials as instruments of long-term quality.
– Process flexibility as a condition for maintaining the core idea in changing realities.

DISCUSSION (WITH COMPARATIVE EXAMPLES)

Perfumiarnia reveals design as a continuous negotiation between vision and realities. The architect's mediating role is central: dialogue with the developer, authorities, community and the site's context – consistent with spaces that prioritise pedestrians and interaction (Gehl, 2014).

Appropriate criteria were selected to compare the spatial and technological solutions used in Perfumiarnia's design. The comparative analysis focused on the following factors:

– Degree of integration with greenery and the landscape.
– Dialogue between modern materials and tradition.
– Solutions that support users and the community.

Three planned-from-scratch facilities were selected for comparative analysis: the residential complex Nowy Strzeszyn and the apartment complex AURA, both located in Poznań (Poland), and Liuzhou Forest City – the so-called green city in Liuzhou (China).

Nowy Strzeszyn by Insomia is a residential ensemble of detached and terraced houses (since 2019) that redefines the model of low-rise housing. Private gardens, pedestrian paths, and shared spaces shape "micro-communities". It is a simple contemporary architecture that merges with greenery (Rumież, 2021).

AURA by KWK Promes and Robert Konieczny is a minimalist apartment complex integrated with a riverside landscape. Terraces and large glazing maximise contact with nature, while green roofs, water retention, and energy-efficient solutions reinforce sustainability (Architektura Murator, 2024; KWK Promes, 2023).

Liuzhou Forest City, designed by Stefano Boeri Architetti, is a green city model featuring vegetated façades and roofs, as well as renewable energy sources, which demonstrates the scalability of architecture and nature integration (ArchDaily, 2017; Stefano Boeri Architetti, 2017).

As a result of the comparison, a few key points can be drawn:

– Integration with nature (Perfumiarnia – Wilson Park; AURA – riverside landscape; Nowy Strzeszyn – private and shared gardens; Liuzhou Forest City – soft green infrastructure).
– Aesthetics and functionality (Perfumiarnia and AURA – contemporary minimalism; Nowy Strzeszyn – coherence amid typological variety; Forest City – hybrids of built form and vegetation).
– Social dimension (openness and the absence of fences at Perfumiarnia, supporting pedestrian flows and everyday activity).

Reflection on Perfumiarnia as a construction project

After in-depth contextual analysis, an essential conclusion about the quality of the implementation of the architectural vision into the Perfumiarnia project can be drawn:

– Context as a starting point. Perfumiarnia continues the story of the Łazarz district; integration with Wilson Park shows that the landscape can co-create quality of life.

– Architecture and nature relationship. The absence of fences and the openness of shared spaces encourage activity and interaction – consistent with the "cities for people" idea (Gehl, 2014).
– Elastic boundary. Movable stainless-steel fabric screens implement the "elastic boundary" pattern, allowing residents to modulate privacy and solar gain (Alexander et al., 2008).
– Process flexibility. Modifications prompted by COVID-19 and cost pressures did not reduce quality – on the contrary, coherence was reinforced through consistent compositional decisions (GUS, 2022; NBP, 2023).
– The architect as a mediator. Negotiation between creative vision and investment, legal and social realities – and the ability to translate ideas into buildable solutions – is decisive.
– Inspiration for future projects. The case confirms the possibility of uniting modernity with history and nature to create spaces of high aesthetic and functional value.

In conclusion, success is determined not by absolute fidelity to the first vision but by the ability to preserve its essence amid changing conditions.

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REFERENCES

Alexander, C., Ishikawa, S., & Silverstein, M. (2008). *Język wzorców. Miasta, budynki, konstrukcja*. Gdańsk: GWP.
ArchDaily (2017). *World's First Vertical Forest City Breaks Ground in China (Liuzhou Forest City / Stefano Boeri Architetti)*. Retrieved from https://www.archdaily.com/874364/worlds-first-vertical-forest-city-breaks-ground-in-china?utm [accessed: 22.09.2025].
Architektura-Murator (2024). *Aura Roberta Koniecznego. Rewolucyjne rozwiązania architektoniczne w Poznaniu – zielony manifest*. Retrieved from https://architektura.muratorplus.pl/projekty/aura-roberta-koniecznego-rewolucyjne-rozwiazania-architektoniczne-w-poznaniu-zielony-manifest-aa-nuec-g5YE-Ek4c.html?utm [accessed: 22.09.2025].
Gehl, J. (2014). *Miasta dla ludzi*. Kraków: Wydawnictwo RAM.
Główny Urząd Statystyczny [GUS]. (2022). *Ceny produkcji budowlano-montażowej – informacje i komunikaty 2020–2022*. Warszawa.
Kodym-Kozaczko, G. (2007). *Rozwój przestrzenny Poznania od połowy XIX do początków XX wieku*. Poznań: Wydawnictwo Naukowe UAM.
KWK Promes (2023). *AURA – opis projektu*. Retrieved from https://www.kwkpromes.pl/aura-2/18110 [accessed: 22.09.2025].
Narodowy Bank Polski [NBP]. (2023). *Informacja o cenach mieszkań i sytuacji na rynku nieruchomości w III kw. 2023 r.* Warszawa.
Palmiarnia Poznańska (2021). *Historia Palmiarni i Parku Wilsona*. Retrieved from https://palmiarnia.poznan.pl/park-wilsona/historia/ [accessed: 22.09.2025].
Poznańskie Klimaty (2020). *Park Wilsona – jeden z najpiękniejszych parków Poznania*. Retrieved from https://www.poznanskieklimaty.pl/park-wilsona-jeden-z-najpiekniejszych-parkow-poznania/?utm [accessed: 22.09.2025].
Rumież, A. (2021, December 22). *Nowy Strzeszyn / Poznań, proj. Insomia*. Retrieved from https://architektura.muratorplus.pl/biblioteka/nowy-strzeszyn-poznan-aa-sKiS-NFAV-oEjL.html?utm [accessed: 22.09.2025].

Stefano Boeri Architetti (2017). *Liuzhou Forest City – project*. Retrieved from https://www.stefanoboeriarchitetti.net/en/project/liuzhou-forest-city/ [accessed: 22.09.2025].
Yin, R. K. (2015). *Studium przypadku w badaniach naukowych. Projektowanie i metody*. Kraków: WUJ.

CZY MARZENIA ARCHITEKTA MOGĄ STAĆ SIĘ RZECZYWISTOŚCIĄ? STUDIUM PRZYPADKU PERFUMIARNI W POZNANIU

STRESZCZENIE

W artykule zaprezentowano studium przypadku budynku mieszkalnego Perfumiarnia w Poznaniu w celu ukazania, jak wizję architektoniczną przełożono na rozwiązania przestrzenne i technologiczne w kontekście dzielnicy Łazarz oraz sąsiedztwa parku Wilsona. Zastosowano analizę kontekstu historycznego i urbanistycznego, analizę projektową oraz interpretację zmian w toku realizacji. Wyniki umożliwiły zaobserwowanie, że jakość architektury wynika z pogłębionej analizy miejsca, integracji z zielenią i świadomych decyzji materiałowo-detalicznych przy zachowaniu spójności urbanistycznej mimo presji rynkowej. W obliczu pandemii COVID-19 i wzrostu kosztów wprowadzono modyfikacje bez rezygnacji z idei, co podkreśla znaczenie elastyczności, negocjacji i współpracy interesariuszy. Perfumiarnia w Poznaniu jest dowodem na to, że „marzenia" projektowe mogą stać się rzeczywistością, jeśli są wsparte analizą kontekstu, pragmatyzmem oraz wrażliwością na uwarunkowania społeczne i ekonomiczne.

Słowa kluczowe: architektura mieszkaniowa, studium przypadku, kontekst, park Wilsona, elastyczność, rewitalizacja

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LOCAL SCOURING PROCESSES AT A PIER ON THE WHITE NILE BRIDGE

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ABSTRACT

This study evaluates global scour prediction models (HEC-18, Froehlich's) for a pier on the White Nile Bridge in Sudan, hypothesising they underestimate scour in tropical rivers with cohesive sediments and dynamic monsoonal flows. Hydrological analysis, HEC-RAS modelling, and sensitivity testing revealed significant discrepancies: the HEC-18 model predicted scour depths of 0.83–1.52 m, while Froehlich's model yielded 1.35–3.18 m. Both were substantially exceeded by a region-specific nonlinear regression model for the Nile (3.24–10.67 m), confirming the hypothesis. The results demonstrate that temperate-derived models fail to capture the White Nile's cohesive clay-silt dynamics and flood-driven sediment transport. This can lead to underestimation, potentially resulting in bridge failure or collapse. The conclusion is that locally calibrated equations and adaptive mitigation strategies are essential for accurate scour risk assessment in tropical rivers.

Keywords: hydraulic structure, bridge, sediment transport, erosion, hydraulic modelling

INTRODUCTION

Rivers are dynamic systems that shape landscapes, transport water and sediment, and sustain ecosystems. They can be formed from various sources, such as rain, snowmelt, springs, or glacial melt, which accumulate and flow downhill due to gravity. Surface runoff, which is water flowing over the ground, erodes small channels (rills) that then join to form streams (Perlman, 2016). Headward erosion is the process by which streams extend upstream by eroding softer rock or soil. This process gradually changes the river's cross-section until it reaches a point of equilibrium. Tectonic uplift creates gradients that direct river courses; for example, the Nile runs in a rift-shaped path, and its White Nile tributary originates from the tectonic basin of Lake Victoria (Talbot & Williams, 2009).

The behaviour, ecological function, and value of rivers are determined by their characteristic attributes, which depend on their geological setting, the climate, and human impact. Channel morphology refers to the shape, structure, and development of the river channel. The drainage basin, or watershed, is the geographical area from which a river system collects precipitation and surface runoff (Latrubesse et al., 2017). Sediment load is a critical physical attribute that affects channel morphology, deltaic development, and ecosystem vitality.

Sediment is carried by rivers in the form of bedload (large particles scraped along the bottom), suspended load (fine clay and silt held in the water column), and dissolved load (ions from chemical weathering)

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(Wang & Yang, 2016). The flow regime defines a river's hydrological attributes, including seasonal peaks, baseflows, and climatically dominated events (Wrzesiński & Graf, 2022). Water quality – an essential hydrological characteristic – describes the chemical, physical, and biological properties of river water (Ejigu, 2021). Rivers are also biodiversity hotspots and ecological powerhouses, supporting rich food webs and specialised environments for aquatic and terrestrial ecosystems (Junk et al., 2018).

Building on the understanding of river dynamics, it is important to examine the specific processes of erosion caused by flowing water. Water scouring is the erosional removal of sediment around hydraulic structures. Oscillatory wake vortices generate low-pressure zones that lift sediment, contributing significantly to scouring. For example, vortices have been shown to account for 30% of storm surge scour at North Sea monopiles (Sumer & Fredsøe, 2002). Scour initiation occurs when the hydrodynamic bed shear stress surpasses the critical limit for sediment entrainment (Van Rijn, 1993). The magnitude of scour is directly influenced by hydraulic factors such as debris, turbulence, unsteady flow, flood magnitude and frequency, and flow depth. Debris in flash floods can decrease scour depth by 0–54.2% by changing flow patterns (Maimun, 2024). Sediment characteristics are also important; cohesive soils (clay/silt) are more resistant to erosion than non-cohesive soils (sand/gravel) due to their cohesive forces and plasticity. A 10% increase in clay content, for instance, results in a 5.5% reduction in scour volume under continuous flow (Boivin, Garnier & Tessier, 2004). Well-graded soils also improve erosion resistance through dense particle packing. Pier geometry controls scour by altering flow patterns. Streamlined shapes (circular, triangular) minimise flow separation and vortex strength, reducing scour depths by 20–40% compared to rectangular piers (Melville & Coleman, 2000; McKeogh & Bekic, 2010a; McKeogh & Bekic, 2010b; McKeogh & Bekic, 2010c). Larger pier widths increase scour by approximately 55% for a doubled width (Lauchlan & Melville, 2001), while a skewed alignment can deepen scour by 1.5 times due to prolonged flow exposure (Richardson & Davis, 2001).

Given these complex factors, a variety of methods have been developed to predict scour. Scour prediction methods are categorised into three types, with empirical models being widely used for their simplicity. These models leverage field or lab data to correlate scour depth with variables like flow velocity, sediment size, and structure geometry. Examples include the standardised HEC-18 formula for bridge piers (Richardson & Davis, 2001), Laursen's live-bed equation, and Breusers' shape-influenced equation. While valuable where data is scarce, such as the modified HEC-18 application for the bimodal Nile sediments at Sudan's Merowe Dam spillway, they can underpredict by 20–40% in complex conditions like the cohesive clay beds at Egypt's Aswan High Dam (Elsaeed, Elsersawy & Ahmed, 2015). To overcome these limitations, hybrids combine empirical foundations with data-driven techniques: the EPRI model achieved 85% accuracy at the Blue Nile's Roseires Dam (Omer et al., 2015), and random forest-enhanced HEC-18 reduced errors below 15% at Ethiopia's Tekeze Dam using satellite data (Gebremichael et al., 2022), though conflicts in Sudan hinder long-term calibration, necessitating future focus on localised data and adaptive methods for climate-altered flow extremes exceeding historical designs.

MATERIAL AND METHODS

The study employed hydrological analysis, geotechnical profiling, and HEC-RAS hydraulic modelling to evaluate scour risk at the planned White Nile Bridge. Three empirical equations: HEC-18, Froehlich's, and a Nile-specific regression were applied, with sensitivity testing performed to assess parameter influence on predicted scour depths.

Study area

The White Nile Bridge – also known as the Omdurman Bridge – is a project that aims to improve traffic congestion between Khartoum and Omdurman by constructing a new bridge. The bridge is located 1,400 m upstream from an existing one on the west bank (approx. 15.604N, 32.482E), and 1,100 m upstream

on the east bank (approx. 15.603N, 32.496E) from another existing bridge. The route starts at Al Arbaeen Road in Omdurman, crosses over the mentioned road, and ends at its connection point with Al Gaaba Road in Khartoum (Japan International Cooperation Agency, 1990; Fig. 1).

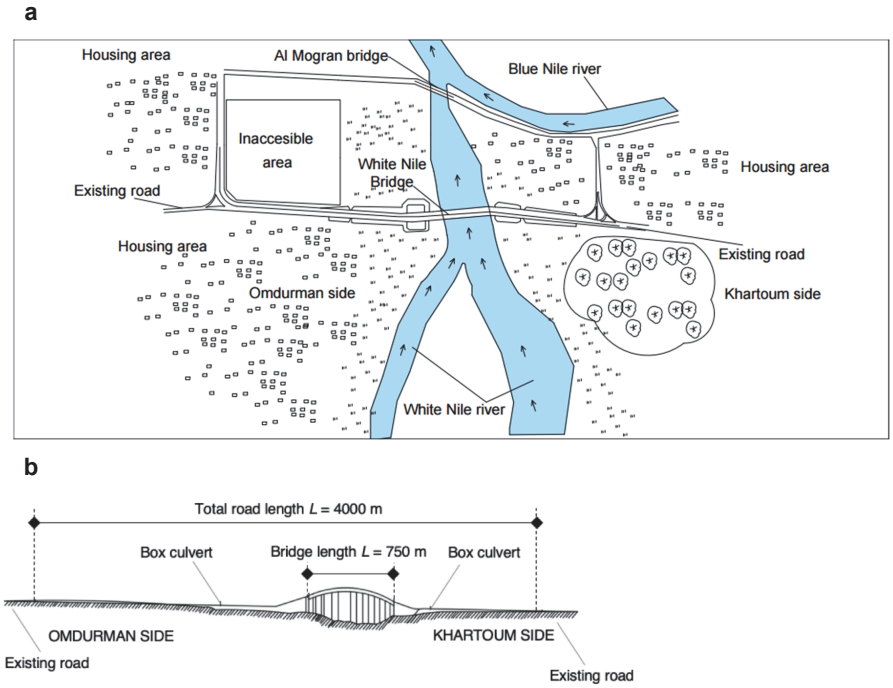


Fig. 1. The White Nile Bridge location, connecting Omdurman and Khartoum: a – plan view, b – profile view

Source: own work.

Hydrological analysis

The White Nile also possesses contrasting hydrological and sediment transport regimes, recording a mean peak discharge of approximately 2.6 million $m^3 \cdot s^{-1}$ in September and flow velocities ranging from 0.35 $m \cdot s^{-1}$ to 1.32 $m \cdot s^{-1}$. Sedimentologically, the river is characterised by pale grey clay and fine silt that account for the pale colour of the river and from which the river derives its name. However, the White Nile contributes less than 20% of the total suspended sediment load to the Nile system at the Mogran confluence because of the smaller grain size and smaller amount of its sediment compared to the coarser, mineral-rich sediments transported by the Blue Nile. This imbalance is also exacerbated by anthropogenic interventions; the construction of the Jebel Aulia Dam has significantly reduced downstream sediment transport via trapping mechanisms, altering natural sediment flux processes. As it stands, the dam's regulation has not only reduced sediment supply to downstream environments but also influenced channel form and agricultural productivity in the region (Japan International Cooperation Agency, 1990).

Subsoil condition

The subsurface profile at the project site consists of alluvial deposits overlying bedrock, with three distinct clay layers identified. The uppermost layer, ACL1 clay (the first layer of clay), is a recent riverbed deposit a few metres thick, exhibiting a very loose, soft consistency with an SPT N-value (standard penetration test) of 1,

indicative of low bearing capacity and high compressibility. Directly beneath this lies ACL2 clay (the second layer of clay), a homogeneous clay containing minor silt content. With an average SPT N-value of 5, this layer demonstrates moderate consistency and shear strength, offering limited stability for lightweight foundations when reinforced. Both layers reflect recent fluvial deposition, with ACL1's instability posing challenges for construction without ground improvement.

The third layer is ACL3 clay (the third layer of clay). This stratum is notably hardened due to desiccation and weathering, resembling a cement-like structure under normal conditions. SPT N-values range from 6 to 11, signalling higher density and load-bearing capacity compared to the upper layers. While stable in dry periods, prolonged flooding may temporarily weaken its integrity. Overall, the stratigraphy transitions from soft, unstable surface sediments to increasingly consolidated materials with depth, positioning ACL3 as the most viable layer for foundational support, provided seasonal hydrological risks are mitigated (Japan International Cooperation Agency, 1990).

HEC-RAS modelling

HEC-RAS, a free and widely used software package from the U.S. Army Corps of Engineers (USACE), employs 1D (Saint-Venant equations) and 2D (shallow water equations) hydrodynamic modelling to simulate river flow, predict flood hazards, design infrastructure, and analyse sediment transport/scour. This study utilised HEC-RAS to develop a rating curve (stage-discharge relationship) for the White Nile, integrating geometric data from satellite DEMs and Google Earth-profiled cross-sections (spaced 250–300 m) throughout the bridge downstream, including bank stations, thalweg elevation, and floodplain boundaries, along with bridge geometry (pier spacing/width) input via its bridge culvert tool (Khalafalla & Ali, 2020). A constant Manning's n = 0.03 was assigned to the channel and floodplain based on the Nile clay bed literature. Steady-flow simulations were executed across four key discharges (370 $m^3 \cdot s^{-1}$, 961.5 $m^3 \cdot s^{-1}$, 2,700 $m^3 \cdot s^{-1}$ and 12,800 $m^3 \cdot s^{-1}$) derived from historical data (Japan International Cooperation Agency, 1990), with upstream discharge boundaries and downstream water surface elevation (WS) boundaries set at 373.54 m, 375.00 m, 376.64 m, and 379.96 m, respectively, generating water surface profiles. The resulting nonlinear rating curve (discharge range of 370–12,800 $m^3 \cdot s^{-1}$) was validated by comparing simulated velocities against recorded velocities at low, normal, and high flows.

Empirical scour models

HEC-18 equation (Johnson & Torrico, 1994)

The Federal Highway Administration manual (HEC-18) is designed to provide information to estimate bridge scour. It's the most widely used equation to predict scouring in clear water channels. It uses the flow velocity, pier width, and sediment size to determine the depth of scouring on the bed of the channel (Eq. 1):

$$y_s = 2K_1K_2K_3\left(\frac{a}{y_1}\right)^{0.65} \mathrm{Fr}^{0.43}, \tag{1}$$

where:
y_s – scour depth [m],
K_1 – correction for the pier nose shape [-] (Table 1),
K_2 – correction for the angle of flow [-] (Table 2),
K_3 – correction for bed conditions [-] (Table 3),
a – pier width [m],
y_1 – flow depth [m],
Fr – Froude's number [-].

Table 1. Correction factors K_1 for different pier nose shapes for the HEC-18 equation

Shape of the pier nose	K_1 [-]
Square nose	1.1
Round nose	1.0
Circular cylinder	1.0
Group of cylinders	1.0
Sharp nose	0.9

Source: Johnson and Torrico (1994).

Table 2. Correction factors K_2 for flow attack angles and pier aspect ratios L/a for the HEC-18 equation

Angle	$L/a = 4$	$L/a = 8$	$L/a = 12$
0°	1.0	1.0	1.0
15°	1.5	2.0	2.5
30°	2.0	2.75	3.5
45°	2.3	3.3	4.3
90°	2.5	3.9	5.0

Source: Johnson and Torrico (1994).

Table 3. Correction factors K_3 for pier scour depth based on bed conditions and dune height H for the HEC-18 equation

Bed condition	Dune height [m]	K_3 [-]
Clear-water scour	not available	1.1
Plane bed and anti-dune flow	not available	1.1
Small dunes	$3.0 > H \geq 0.6$	1.1
Medium dunes	$9.2 > H \geq 3.0$	1.2–1.1
Large dunes	$H \geq 9.2$	1.3

Source: Johnson and Torrico (1994).

Froehlich's equation (Froehlich, 1988)

Froehlich's equation was developed by obtaining data from various publications, assuming the uniformity of the sediment and taking into account the median grain size of the riverbed. To correct imperfections and errors, a factor of safety has been assumed to determine the maximum scour depth (Eq. 2):

$$\frac{d_s}{a} = 0.32\,\phi \left(\frac{a'}{a}\right)^{0.62} \left(\frac{y_1}{a}\right)^{0.46} \mathrm{Fr}^{0.20} \left(\frac{a}{d_{50}}\right)^{0.08}, \tag{2}$$

where:
d_s – depth of local scour measured from a projected stream elevation [m],
ϕ – shape factor [-] (Table 4),
a' – pier width projected into the flow direction [m],
Fr – Froude's number [-],
d_{50} – median grain size of the riverbed material [m].

Table 4. Correction factors ϕ for pier shape for Froehlich's equation

Shape of the pier	ϕ [-]
Square nose	1.3
Round nose	1.0
Sharp nose	0.7

Source: Froehlich (1988).

Nile nonlinear regression analysis equation (Helal, El Sersawy & Abdelbaky, 2022)

This equation was developed by a team of engineers at Menoufia University in Egypt. It was created by analysing actual scouring data of the Nile in Egypt using SPSS software. The equation showed more accurate results for both steady and unsteady flow. The equation was given as follows (Eq. 3):

$$y_s = \frac{AQ^{0.203}V_m^{1.087}}{d_{50}^{1.805}y_{max}^{0.635}S_e^{0.073}y_1^{0.489}T^{0.156}}, \tag{3}$$

where:
A – constant parameter; $A = 4.36 \cdot 10^{-6}$ [-],
Q – water discharge [$m^3 \cdot s^{-1}$],
V_m – average velocity of flow [$m \cdot s^{-1}$],
y_{max} – maximum channel flow depth [m],
S_e – bed slope [-],
T – top width of the channel [m].

Sensitivity analysis

Sensitivity analysis was performed to quantify the effect of certain input parameters on predictions of scour depth and to test the robustness of the empirical models under Sudan's evolving hydrological and geotechnical conditions. Some of the key variables tested included flow velocity, each of which was systematically varied within realistic ranges based on historical data and regional literature (Eq. 4):

$$\Delta x = \frac{x_2 - x_1}{x_1}100\%, \tag{4}$$

where:
Δx – percentage of change in the value [%],
x_1 – certain value,
x_2 – estimated value.

The relative influence of key input parameters on the predicted scour depth (y_s) was calculated by analysing the flow depth (y_1) and the flow velocity (v), which are hydraulically linked through the stage-discharge rating curve developed in HEC-RAS. To isolate the effect of flow depth, y_1 was incrementally increased by 10 cm (0.1 m). As the water surface elevation changes, the linked flow velocity (v) also changes proportionally based on the cross-sectional geometry; therefore, a 10 cm increase in flow depth simultaneously induces a corresponding small increase in the velocity (Eq. 5):

$$\%x = \frac{\Delta x}{\Sigma \Delta X}100, \tag{5}$$

where:
$\%x$ – percentage of influence of an input,
Δx – change of one step of the input,
$\sum \Delta X$ – summation of the change of input in the equation.

RESULTS

HEC-18 equation results

Three main flow scenarios were used to calculate the HEC-18 scour depths (y_s): lowest, normal, and highest, representing the hydrological variability of the White Nile and utilising a rating curve created by the HEC-RAS computer to mimic the progression of flood stages through incremental adjustments in water level. Historical discharge records served as the basis for these scenarios. The analysis's main conclusion was that there was a definite inverse link between scour depth (y_s) and flow depth (y_1). Predicted scour is increased at shallower depths because flow velocity becomes more concentrated close to the riverbed. For instance, the estimated scour depth reached y_s = 1.524 m under the lowest flow circumstances (y_1 = 1.87 m), indicating severe localised turbulence. In contrast, the scour depth decreased to y_s = 0.83 m (45% decrease) under the greatest flow scenario (y_1 = 8.17 m) since the deeper flow dispersed energy throughout a larger cross-sectional area, mitigating erosive forces (Fig. 2). Despite higher velocities during peak flows (e.g., v = 1.35 m·s^{-1}), the dominant influence of y_1 suppresses scour depth (Tables 5 and 6).

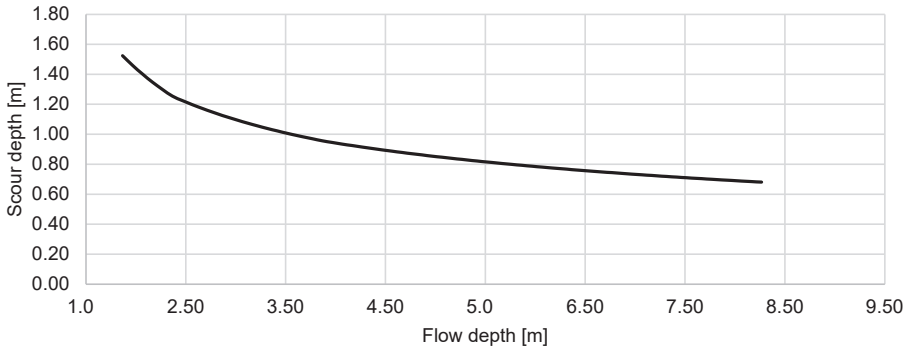


Fig. 2. The relationship between flow depth and predicted scour depth using the HEC-18 equation

Source: own work.

Table 5. Calculation of the scour using the HEC-18 equation

Water level	y_1 [m]	K_1 [-]	K_2 [-]	K_3 [-]	a [m]	v [ms^{-1}]	y_s [m]	Fr [-]	Q [m^3·s^{-1}]
Lowest flow	1.87	1.1	1.0	1.1	4.8	0.35	1.52	0.082	370.0
Normal flow	3.34	1.1	1.0	1.1	4.8	0.52	1.09	0.091	961.5
Highest flow	8.30	1.1	1.0	1.1	4.8	1.35	0.75	0.150	12,800.0

y_1 – flow depth, K_1 – correction for the pier nose shape, K_2 – correction for the angle of flow, K_3 – correction for bed conditions, a – pier width, v – flow velocity, y_s – scour depth, Fr – Froude's number, Q – water discharge.

Source: own work.

The sensitivity analysis revealed that flow depth (y_1) emerged as the most influential parameter, governing approximately 90% of the variability in predicted scour depths across all models. This dominance stems from the inverse relationship between y_1 and scour magnitude: deeper flows reduce shear stress concentration around the pier, thereby dampening erosion potential (Table 6).

Table 6. Calculation of the sensitivity analysis

$y_{1\text{-}1}$ [m]	$y_{1\text{-}2}$ [m]	Δy_1 [m]	v_1 [m·s^{-1}]	v_2 [m·s^{-1}]	Δv [m·s^{-1}]	$y_{s\text{-}1}$ [m]	$y_{s\text{-}2}$ [m]	Δy_s [m]	y_1 [%]
3.5	3.6	0.1	0.48	0.49	0.01	1.0000	0.9800	−0.0140	90.7
3.6	3.7	0.1	0.49	0.50	0.01	0.9840	0.9700	−0.0140	90.7
3.7	3.8	0.1	0.50	0.51	0.01	0.9700	0.9560	−0.0130	90.7
3.8	3.9	0.1	0.51	0.52	0.01	0.9560	0.9450	−0.0110	89.0
3.9	4.0	0.1	0.52	0.53	0.01	0.9450	0.9350	−0.0100	88.7
4.0	4.1	0.1	0.54	0.50	0.01	0.9350	0.9248	−0.0100	88.7
4.1	4.2	0.1	0.55	0.56	0.01	0.9250	0.9150	−0.0098	88.7
4.2	4.3	0.1	0.56	0.58	0.01	0.9150	0.9055	−0.0095	88.7

$y_{1\text{-}1}$ – the first flow depth, $y_{1\text{-}2}$ – the second flow depth, Δy_1 – the difference between the first and the second flow depth, v_1 – the velocity of the first flow, v_2 – the velocity of the second flow, Δv – the difference between the first and the second water velocity, $y_{s\text{-}1}$ – the predicted scour depth for the first flow, $y_{s\text{-}2}$ – the predicted scour depth for the second flow, Δy_s – the difference between the first and the second scour depth, y_1 – the flow depth.

Source: own work.

In contrast, pier geometry correction factors (K_1, K_2, K_3), held constant throughout the analysis (K_1 = 1.1, K_2 = 1, K_3 = 1.1), introduced potential underestimations in complex flow scenarios. While these constants simplified calculations, they failed to account for dynamic real-world factors such as debris accumulation or evolving bedforms.

Froehlich's equation results

Froehlich's equation predicted consistently higher scour depths (d_s) than HEC-18, emphasising its sensitivity to sediment properties (d_{50} = 0.0002 m) and flow alignment (Table 7).

Table 7. Key results of Froehlich's equation for the lowest, normal, and highest flows

Flow scenario	y_1 [m]	Fr [-]	d_s [m]
Lowest flow	1.87	0.082	1.35
Normal flow	3.34	0.091	1.80
Highest flow	8.30	0.191	3.18

y_1 – flow depth, Fr – Froude's number, d_s – depth of local scour measured from a projected stream elevation.

Source: own work.

In contrast to HEC-18, scour depth exhibited a direct correlation with flow depth (y_1), reaching its maximum value of 3.18 m at the highest flow depth: y_1 = 8.30 m. This trend underscores the model's core emphasis on sediment transport capacity (Fig. 3). Scour depth increased with higher Froude's number (Fr) values, particularly during peak flows, consistent with Froehlich's established relationship between scour and flow intensity (Fig. 4).

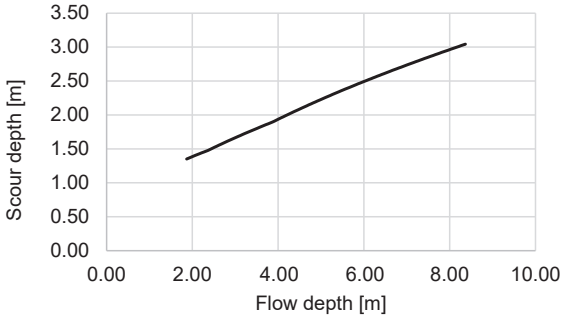


Fig. 3. The predicted scour and flow depth using Froehlich's equation

Source: own work.

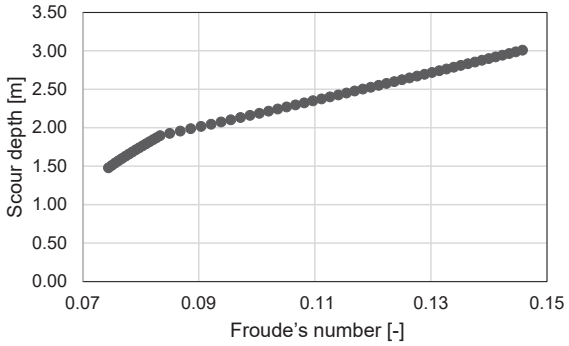


Fig. 4. Relationship between Froude's number value and predicted scour depth based on Froehlich's equation

Source: own work.

Nile nonlinear regression equation results

The Nile-specific equation, calibrated for regional sediment dynamics (d_{50} = 0.2 mm, S_e = 0.0014), yields significantly higher scour depths. This model incorporates monsoonal discharge variability (Q), maximum flow depth (y_1 = 8.296 m), and bed slope (S_e), revealing the White Nile's capacity to mobilise fine sediments during floods. The exponential rise in y_s with Q underscores the compounding effects of velocity and sediment load in Sudan's riverine environment (Table 8).

Table 8. Nile nonlinear regression equation calculation for the lowest, normal, and highest flow

A [-]	Q [$m^3 \cdot s^{-1}$]	V_m [$m^2 \cdot s^{-1}$]	d_{50} [m]	y_{max} [m]	S_e [-]	y_1 [m]	T [m]	y_s [m]
0.00000436	370.0	0.35	0.0002	8.30	0.0014	1.87	119.06	3.24
0.00000436	961.5	0.52	0.0002	8.30	0.0014	3.34	136.13	4.46
0.00000436	12,800.0	1.35	0.0002	8.30	0.0014	8.30	650.07	10.67

A – constant parameter, Q – water discharge, V_m – average velocity of flow, d_{50} – median grain size of the riverbed material, y_{max} – maximum channel flow depth, S_e – bed slope, y_1 – flow depth, T – top width of the channel, y_s – scour depth.

Source: own work.

Comparative analysis of models

The evaluation revealed significant disparities in model performance, directly tied to their underlying assumptions. HEC-18 consistently underestimated scour depths (0.83–1.52 m) compared to Froehlich's equation (1.35–3.18 m), highlighting its inherent bias toward non-cohesive sediments and a steady-state flow conditions approach misaligned with the White Nile's cohesive clay soil and dynamic monsoonal hydrology. While Froehlich's equation better captured Sudan's cohesive sediment dynamics through its explicit incorporation of grain size and flow intensity, its predictions remained conservative relative to field-validated outcomes, constrained by the absence of localised calibration for region-specific factors like seasonal sediment pulsing. Crucially, the Nile-specific nonlinear regression model (Helal et al., 2022) outperformed both, predicting scour depths of 3.24–10.67 m (Fig. 5). It demonstrates the importance of regionally calibrated equations that can adequately quantify scour risk in tropical rivers with complex sediment-transport regimes.

To assess the efficacy and applicability of various scour prediction methods under different hydraulic conditions, a scenario-based comparison was conducted. The predicted scour depths (y_s) were calculated using three distinct methodologies: HEC-18, Froehlich's equation, and a specialised Nile-specific equation. These predictions are presented for three critical flow scenarios – lowest, normal, and highest flow – derived from the Nile model, offering insights into how each method estimates scour under varying flow regimes pertinent to the Nile's hydrological characteristics (Table 9).

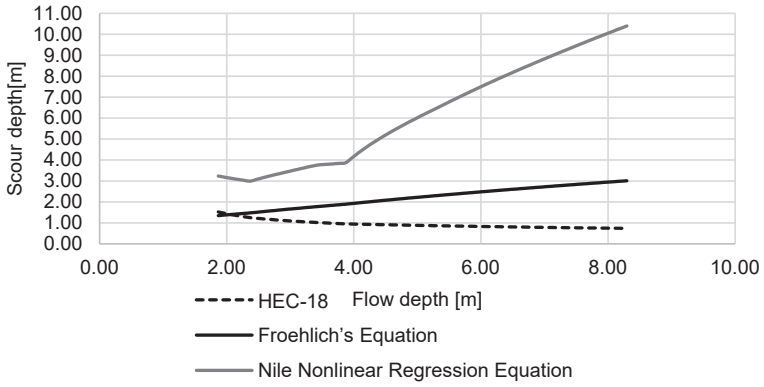


Fig. 5. Scour depth predictions versus flow depth using three methods: HEC-18, Froehlich's equation, and a Nile-specific nonlinear regression model

Source: own work.

Table 9. Predicted scour depths under different flow scenarios using HEC-18, Froehlich's equation, and the Nile-specific equation, showing scour estimates under flow from the Nile model

Flow scenario	Scour depth [m]		
	HEC-18 equation (y_s)	Froehlich's equation (d_s)	Nile-specific equation (y_s)
Lowest flow	1.52	1.35	3.24
Normal flow	1.09	1.80	4.46
Highest flow	0.83	3.18	10.67

Source: own work.

CONCLUSIONS

This study examined the applicability of global scour prediction models to Sudan's White Nile, revealing significant discrepancies in scour depth estimates. The central hypothesis guiding this research posited that globally derived empirical scour prediction models, developed primarily for temperate rivers with non-cohesive sediment and stable flows, would systematically underestimate actual scour depths in the dynamic, cohesive, and highly variable conditions of the White Nile. The HEC-18 model, widely used for bridge scour prediction, consistently underestimated scour depths (ranging from 0.83 to 1.52 m) due to its reliance on non-cohesive sediment assumptions and steady-flow conditions, which poorly align with the Nile's cohesive clay-silt mixtures and monsoonal flow variability. Froehlich's equation, while more sensitive to sediment properties, produced moderate predictions (1.35–3.18 m) but lacked calibration for the Nile's unique sediment dynamics. In contrast, the Nile-specific nonlinear regression model, incorporating localised parameters such as median sediment size (d_{50} = 0.2 mm), monsoonal discharge variability, and bed slope, predicted significantly higher scour depths (3.24–10.67 m). These findings strongly support our hypothesis, unequivocally demonstrating that temperate-derived models fall short in accurately predicting scour in tropical river systems like the White Nile. These results align with the White Nile's high sediment mobility during flash floods, underscoring the limitations of temperate-derived models.

The study faced several constraints. First, data scarcity stemming from outdated hydrological records and limited real-time sediment monitoring restricted model calibration and validation. Reliance on satellite-derived proxies introduced uncertainties, particularly in capturing subsurface sediment heterogeneity. Second, simplified assumptions in empirical models, such as constant correction factors (K_1, K_2, K_3) for pier geometry and bed conditions, overlook dynamic factors like debris accumulation and evolving bedforms, leading to potential underestimations. Third, the geographical focus on the White Nile Bridge limits the generalisability of findings to other Nile tributaries or arid wadis in Sudan, which exhibit distinct sediment and flow regimes. These limitations highlight the challenges of applying global frameworks to data-scarce, climate-vulnerable regions.

Future research should focus on expanding data collection through real-time gauging stations and sediment traps along the Nile to refine model inputs and validate satellite-derived hydrology. Hybrid approaches, integrating machine learning with empirical equations, could better capture nonlinear interactions between sediment transport and flow dynamics. Regional collaboration under initiatives like the Nile Basin Initiative is essential to harmonise transboundary sediment management and share hydrological datasets. Field testing of adaptive mitigation measures, such as gabion check dams in ephemeral wadis or sacrificial piles at high-risk bridges, would provide practical insights into cost-effective, locally tailored solutions. Expanding the scope to include other Nile tributaries and arid river systems would enhance the applicability of scour prediction frameworks across Sudan's diverse hydrological landscapes.

Development of specialised models for cohesive sediments is necessary due to the unique cohesive clay-silt mixtures of the White Nile. Integration of remote sensing and GIS for long-term monitoring is also essential. Economic feasibility studies of mitigation strategies should be included to ensure the most cost-effective and sustainable solutions are adopted. Capacity building and knowledge transfer strategies should be focused on within local engineering communities and institutions in Sudan.

Authors' contributions

Conceptualisation: M.K. and M.E.; methodology: M.E.; formal analysis: M.E.; writing – original draft preparation: M.E.; writing – review and editing: M.K. and M.E.; supervision: M.K.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Boivin, P., Garnier, P. & Tessier, D. (2004). Relationship between clay content, clay type, and shrinkage properties of soil samples. *Soil Science Society of America Journal*, *68* (4), 1145–1153.

Ejigu, M. T. (2021). Overview of water quality modeling. *Cogent Engineering*, *8* (1), 1891711.

Elsaeed, G., Elsersawy, H. & Ibrahim, M. (2015). *Scour Evaluation at the Nile River Bends on Rosetta Branch*. LAP Lambert Academic Publishing.

Froehlich, D. C. (1988). Analysis of onsite measurements of scour at piers. In *Hydraulic engineering: proceedings of the 1988 national conference on hydraulic engineering* (pp. 534–539). New York: ASCE.

Gebremicael, T. G., Deitch, M. J., Gancel, H. N., Croteau, A. C., Haile G. G., Beyene, A. N. & Kumar, L. (2022). Satellite-based rainfall estimates evaluation using a parsimonious hydrological model in the complex climate and topography of the Nile River Catchments. *Atmospheric Research*, *266*, 105939. https://doi.org/10.1016/j.atmosres.2021.105939

Helal, E., El Sersawy, H. & Abdelbaky, M. (2022). Evaluation of the predictive performance of general scour equations along the Nile River. *ISH Journal of Hydraulic Engineering*, *28* (S1), 366–379. https://doi.org/10.1080/09715010.2019.1668307

Japan International Cooperation Agency. (1990). *The feasibility study on the construction of the New White Nile Bridge in the Republic of the Sudan: Main report* (Report 52). Tokyo: Japan International Cooperation Agency.

Johnson, P. A. & Torrico, E. F. (1994). Scour around wide piers in shallow water. *Transportation Research Record*, *1471*, 66–70.

Junk, W. J., Piedade, M. T. F., Lourival, R., Wittmann, F., Kandus, P., Lacerda, L. D., Bozelli, R. L., Esteves, F. A., Nunes da Cunha, C., Maltchik, L., Schöngart, J., Schaeffer-Novelli, Y. & Agostinho, A. A. (2014). Brazilian wetlands: their definition, delineation, and classification for research, sustainable management, and protection. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *24* (1), 5–22. https://doi.org/10.1002/aqc.2386

Khalafalla, E. E. & Ali, A. H. M. (2020). Inspection and rehabilitation of old White Nile steel bridge substructure. *FES Journal of Engineering Sciences*, *9* (1), 57–64. https://doi.org/10.52981/FJES.V9I1.659

Latrubesse, E. M., Arima, E. Y., Dunne, T., Park, E., Baker, V. R., d'Horta, F. M., Wight, C., Wittmann, F., Zuanon, J., Baker, P. A., Ribas, C. C., Norgaard, R. B., Filizola, N., Ansar, A., Flyvbjerg, B. & Stevaux, J. C. (2017). Damming the rivers of the Amazon basin. *Nature*, *546* (7658), 363–369. https://doi.org/10.1038/nature22333

Lauchlan, C. S. & Melville, B. W. (2001). Riprap protection at bridge piers. *Journal of Hydraulic Engineering*, *127* (5), 412–418. https://doi.org/10.1061/(ASCE)0733-9429(2001)127:5(412)

Maimun, R. (2024). Experimental study on Local Scour around Bridge Pier Models generated by Flash Floods carrying Debris. *IOP Conference Series: Earth and Environmental Science*, *1343* (1), 012028. https://doi.org/10.1088/1755-1315/1343/1/012028

McKeogh, E. & Bekic, D. (2010a). *Malahide Viaduct Reinstatement. Technical Paper 1. Collapse Mechanism and Initial Emergency Works*. Cork: Flood Study Group University College Cork.

McKeogh, E. & Bekic, D. (2010b). *Malahide Viaduct Reinstatement. Technical Paper 2. Physical Models*. Cork: Flood Study Group University College Cork.

McKeogh, E. & Bekic, D. (2010c). *Malahide Viaduct Reinstatement. Technical Paper 3. Computer Models and Hybrid Modelling*. Cork: Flood Study Group University College Cork.

Melville, B. W. & Coleman, S. E. (2000). *Bridge scour*. Colorado: Water Resources Publication.

Omer, A. Y. A., Ali, Y. S. A., Roelvink, J. A., Dastgheib, A., Paron, P. & Crosato, A. (2015). Modelling of sedimentation processes inside Roseires Reservoir (Sudan). *Earth Surface Dynamics*, *3* (2), 223–238. https://doi.org/10.5194/esurf-3-223-2015

Perlman, H. (2016). *The water cycle*. USGS Water Science School. Retrieved from https://water.usgs.gov/edu/watercycle.html [accessed: 18.05.2017].

Richardson, E. V. & Davis, S. R. (2001). *Evaluating scour at bridges* (FHWA-NHI-01-001). (4 ed.). Federal Highway Administration.

Sumer, B. M. & Fredsøe, J. (2002). *The mechanics of scour in the marine environment*. World Scientific Publishing Company. https://doi.org/10.1142/4942

Talbot, M. R. & Williams, M. A. (2009). Cenozoic evolution of the Nile Basin. In H. Dumont (Ed.), *The Nile: Origin, environments, limnology and human use* (pp. 37–60). Springer Science + Business Media. Springer Science + Business Media. https://doi.org/10.1007/978-1-4020-9726-3_3

Van Rijn, L. C., Nieuwjaar, M. W., Kaay, T. van der, Nap, E. & Kampen, A. van (1993). Transport of fine sands by currents and waves. *Journal of Waterway, Port, Coastal, And Ocean Engineering*, *119* (2), 123–143.

Wang, Q. & Yang, Z. (2016). Industrial water pollution, water environment treatment, and health risks in China. *Environmental Pollution*, *218*, 358–365. https://doi.org/10.1016/j.envpol.2016.07.011

Wrzesiński, D. & Graf, R. (2022). Temporal and spatial patterns of the river flow and water temperature relations in Poland. *Journal of Hydrology and Hydromechanics*, *70* (1), 12–29. https://doi.org/10.2478/johh-2021-0033

PROCESY LOKALNEGO ROZMYCIA PRZY FILARZE MOSTU NA BIAŁYM NILU

STRESZCZENIE

Niniejsze badanie ocenia globalne modele prognozowania rozmycia (HEC-18, Froehlicha) dla filara mostu na Białym Nilu w Sudanie, stawiając hipotezę, że dochodzi w nich do niedoszacowania rozmycia w rzekach tropikalnych z osadami kohezyjnymi i dynamicznymi przepływami monsunowymi. Analiza hydrologiczna, modelowanie HEC-RAS oraz testy wrażliwości ujawniły istotne rozbieżności: model HEC-18 przewidywał głębokości rozmycia na poziomie 0,83–1,52 m, podczas gdy model Froehlicha dawał wartości 1,35–3,18 m. Oba wyniki zostały znacząco przekroczone przez regionalny nieliniowy model regresyjny, opracowany dla Nilu (3,24–10,67 m), co potwierdziło postawioną hipotezę. Wyniki pokazują, że modele wywodzące się z klimatów umiarkowanych nie uwzględniają dynamiki kohezji iłowo-mułowej oraz transportu rumowiska. W konsekwencji dochodzi do niedoszacowania, co potencjalnie może doprowadzić do awarii lub katastrofy budowlanej mostu. Do dokładnej oceny ryzyka rozmycia w rzekach tropikalnych są niezbędne lokalnie skalibrowane równania i adaptacyjne strategie zabezpieczające.

Słowa kluczowe: budowla hydrotechniczna, most, transport rumowiska, erozja, modelowanie hydrauliczne

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ORIGINAL PAPER

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MUSTERHOLZBAURICHTLINIE (MHolzBauRL) AS A TOOL FOR SHAPING MULTI-STOREY TIMBER BUILDINGS IN GERMANY

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ABSTRACT

Given increasingly stringent climate requirements, timber is once again emerging as a low-emission material for medium- and high-rise buildings; however, its inherent combustibility still limits widespread adoption. This paper critically analyses the MHolzBauRL – guidelines implemented in selected German *Länder* – as an integrated legal-technical instrument for designing multi-storey timber structures that meet the REI 60 and REI 90 fire-resistance classes. We outline the scope and hierarchy of the regulations, explain the principles in detail and compare them with DIN 4102. A review of completed projects reveals that the guidelines streamline approval procedures and enhance investor confidence in engineered timber. We conclude that the MHolzBauRL provides coherent and unambiguous criteria for the safe construction of tall timber buildings, and we highlight the need for broader regulatory harmonisation – including the potential adoption of similar variants in Poland.

Keywords: MHolzBauRL, timber construction, fire safety, multi-storey buildings

INTRODUCTION

In recent years, due to climate change and efforts to reduce concrete usage, timber has re-emerged as a promising material for multi-storey construction (Gustavsson & Sathre, 2011; Churkina et al., 2020). Wood's renewability and lower carbon footprint promote its application in sustainable architecture (Li, Lei, Wu & Yan, 2017). However, its inherent combustibility poses significant challenges, compounded by low awareness of fire safety solutions for timber structures and a general lack of trust in the material's performance (Zang et al., 2023). The *Musterholzbaurichtlinie* (MHolzBauRL) serves as a crucial regulatory framework in Germany, enabling the safe design and implementation of multi-storey timber buildings by addressing these fire safety concerns. This study aims to analyse the role of the MHolzBauRL in facilitating timber construction, focusing on fire protection requirements and the combustible nature of wood.

In Germany, building regulations classify structures into five categories (*Gebäudeklassen*, GK1–GK5) according to their height and occupancy, as outlined in the *Musterbauordnung* (Bauministerkonferenz, 2024a). Classes 1–3 cover low-rise buildings, where the minimum fire resistance requirement is REI 30. Class 4 applies to mid-rise buildings up to approximately 13 m, requiring REI 60 fire resistance. Class 5 includes high-rise buildings with no height limit, where REI 90 must be ensured. These classes provide the legal framework for defining fire safety objectives, evacuation times and permissible structural

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solutions. The MHolzBauRL is of particular significance because it explicitly enables combustible materials such as timber to be used for structural elements in Classes 4 and 5, provided that the assemblies meet the prescribed REI 60 or REI 90 criteria.

Wood as a response to the climate crisis

In the face of the escalating climate crisis and the urgent search for low-carbon building materials, wood is gaining renewed attention as a construction material of the future. Its low embodied carbon, ability to store carbon dioxide and renewable nature position it as one of the most promising solutions for climate--conscious architecture.

Compared to conventional building materials such as concrete or steel, wood stands out not only for its environmental performance, but also for its recyclability and biodegradability. However, the use of timber in multi-storey buildings remains limited, primarily due to concerns about fire safety and regulatory barriers (Ljunggren, Fredriksson, Johansson & Sasic Kalagasidis, 2025).

Germany has embraced a progressive and systematic approach to sustainability through *Klimaschutz*[1] (climate protection) policies. Introduced in the early 1990s and strengthened significantly with the Climate Protection Plan 2050 (*Klimaschutzplan 2050*, adopted in 2016), these strategies aim to drastically reduce greenhouse gas emissions across all sectors – including the construction industry. In this context, timber construction is actively promoted as a key measure for achieving climate targets.

In recent years, Germany has seen a surge in mid- and high-rise timber buildings, supported by public procurement policies, research programmes and a growing social awareness around sustainability. These efforts exemplify how *Klimaschutz* policies translate into practical architectural outcomes.

One of the tools for promoting timber construction in Germany is the set of guidelines called the *MHolzBauRL*, which are gradually being implemented into state law (*Landesrecht*) as 'Technical Building Regulations' (*Technische Baubestimmungen*) – a type of technical building regulation that will be discussed in more detail later in the publication.

LITERATURE REVIEW

The topic of fire-safe timber construction has attracted increasing scholarly and professional attention in recent years, particularly in the context of climate change and the sustainable transformation of the building industry (Buchanan & Abu, 2016). This literature review identifies and discusses key works that have informed the analysis presented in this study, focusing on four thematic areas: (1) sustainable construction and timber as a low-carbon material; (2) the fire behaviour of timber structures; (3) German fire safety standards; and (4) case studies of completed timber buildings.

Within the field of Timber and Sustainable Architecture (1) and the fire behaviour of timber structures, several influential researchers and institutions from Germany have significantly contributed to advancing the discourse on sustainable timber construction (Hopkin et al., 2024; Perković et al., 2024). Notable among them are S. Hofmeister, H. Kaufmann, S. Winter, A. Hafner, W. Huss, M.W. Lennartz and S. Jacob-Freitag (Lennartz & Jacob-Freitag, 2015; Huß, Kaufmann & Merz, 2019; Hofmeister, 2022; Kaufmann, Krötsch & Winter, 2024). (2) The German fire safety regulatory landscape is defined by documents such as the *Musterbauordnung* (Bauministerkonferenz, 2024a), *Musterholzbaurichtlinie* (Bauministerkonferenz,

[1] *Klimaschutz* is the German term for climate protection and, in Germany, it represents a comprehensive national strategy aimed at reducing greenhouse gas emissions, promoting sustainable development and transitioning towards a low-carbon economy. Unlike in many other countries, *Klimaschutz* in Germany is not just a political slogan – it is a legally anchored, multi-sectoral framework with concrete targets, action plans and accountability mechanisms.

2020; Bauministerkonferenz, 2021; Bauministerkonferenz, 2024b), DIN 4102[2] (Deutsches Institut für Normung [DIN], 2016) and DIN EN 13501-1 (DIN, 2019), which specify classifications for material behaviour and structural fire resistance. (3) Case studies of completed projects have been documented in architectural journals (e.g. Detail, Bauwelt, BBB) and building technology publications.

The first version of MHolzBauRL was introduced in 2004 under the title 'Model Guideline on Fire Protection Requirements for Highly Fire-Resistant Components in Timber Construction' (*Muster-Richtlinie über brandschutztechnische Anforderungen an hochfeuerhemmende Bauteile in Holzbauweise*, M-HFHHolzR). This guideline was later replaced in 2020 by the Model Timber Construction Guideline (*Muster-Holzbaurichtlinie*, MHolzBauRL). Since the adoption of the guideline, several multi-storey timber projects have been completed in Germany that illustrate its practical implementation. These include the seven-storey *Skaio* residential tower in Heilbronn (Kaden+Lager 2019), documented in detail and recognised as Germany's first official timber high-rise. Other examples are the hybrid office and conference building *Luisenblock* in Berlin (Sauerbruch Hutton 2021), the cooperative housing project *Quartier WIR* in Berlin-Weißensee (Deimel Oelschläger Architekten 2020) and the *Walden 48* apartment building in Berlin-Friedrichshain (Scharabi Architekten 2020). These projects were widely reported in Bauwelt and DBZ – not only for their architectural merit, but also because their approval processes relied on the clear and proven guidance of the MHolzBauRL. By systematically applying measures such as non-combustible cladding, cavity compartmentation and controlled service routing, these case studies demonstrate how the guideline facilitated compliance with REI 60/90 requirements in Classes 4 and 5 (O'Hegarty, Kinnane, Newell & West, 2021).

MATERIAL AND METHODS

Growing interest in medium- and high-rise timber construction in Germany collides with the need to satisfy stricter fire safety classes (REI 60/90) than those traditionally required for low-rise buildings (REI 30). This article, therefore, investigates whether the MHolzBauRL – a set of design guides introduced since 2004 – offers a sufficiently robust regulatory and technical framework for safe multi-storey timber buildings. Our inquiry combines: (i) qualitative analysis of the guideline's legal text, DIN cross-references and associated commentary; (ii) a review of national fire safety legislation and approval pathways; and (iii) case studies of completed German timber buildings erected after 2004 that apply the MHolzBauRL. Through this mixed documentary and case-based approach, we assess how the guideline translates into detailed rules, approval times and built performance. The paper maps the evolution of the regulation, benchmarks it against DIN 4102-4 (DIN, 2016) and Eurocode provisions and discusses its strengths, limitations and transferability to other jurisdictions, notably Poland.

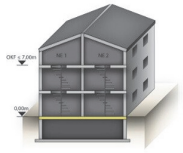
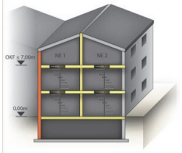
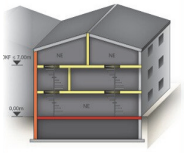
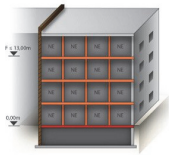
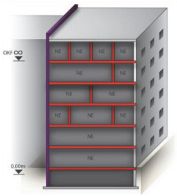
Classification of buildings in Germany according to §52

In Germany, buildings are classified into five main classes and one subclass according to §52 of the Model Building Code (MBO), primarily based on their height. This classification serves as a basis for applying specific fire protection requirements to ensure safety. The five main classes are Class 1 (GK1) through Class 5 (GK5). Each class corresponds to a required minimum fire resistance rating, expressed in terms of REI (acronym for resistance, integrity, insulation) values ranging from REI 30 to REI 90. Specifically, Classes 1 and 2 typically require lower fire resistance ratings, Class 3 (GK3) requires REI 30, Class 4 (GK4) requires

[2] DIN 4102 defines the classification of building materials and structural elements based on their fire performance properties. It specifies which materials are non-combustible, which are combustible and describes their properties related to ignition, flame spread and fire sustainment. It is useful in designing timber partitions to the REI 30 and REI 60 standards.

REI 60 and Class 5 (GK5) demands the highest fire resistance of REI 90. The maximum fire resistance requirement, REI 90, ensures the highest level of fire resistance by maintaining load-bearing capacity, fire integrity and thermal insulation for at least 90 min. This classification and its corresponding fire resistance ratings are illustrated in detail in Table 1.

Table 1. Classification of buildings in Germany according to §52 MBO, taking building height into account. Height (h) within the meaning of Sentence 1 refers to the height of the upper edge of the floor of the highest occupied room above the average ground level

GK 1a	GK 1b	GK 2	GK 3	GK 4	GK 5
					
h = 7 m	h = 7 m	h = 7 m	h = 7 m	h = 13 m	h = ∞
detached building, maximum of two dwelling units, without a basement, with up to 400 m^2 per dwelling unit	detached building, agricultural and forestry use	not detached, maximum of two dwelling units, up to 400 m^2 per dwelling unit, without a basement	special building, maximum zone 400 m^2	maximum zone 400 m^2 without a basement	maximum zone 400 m^2 without a basement

Source: own work based on the MBO and the illustrations and information compiled by Cornelia Halbach, brandschutz plus GmbH.

For this publication, buildings of Classes 1–3 are considered low-rise according to the Polish ministerial regulation on technical conditions and their location. Class 4 buildings are mid-rise, while Class 5 buildings are high-rise and tall buildings.

Timber as a structural material and fire protection challenges

Compared to reinforced concrete, masonry and steel, wood is combustible and, therefore, contributes to the fire load of a building. This, combined with its unfortunate historical reputation dating back to the Middle Ages and building regulations that have not always kept pace with modern technological solutions, has raised doubts regarding the use of wood as a structural material.

However, it is essential to emphasise that the risk of fire does not fundamentally depend on the material used in the building's structure. Experience clearly shows that the risk of fire in residential buildings is not linked to the structural materials, but rather results from defects in technical installations and human error. Structural wood, as a combustible material, does not inherently pose a fire risk or cause fire ignition.

At this point, it is crucial to distinguish between the flammability of building materials (classified according to fire behaviour classes) and the fire resistance of building elements (classified according to fire resistance ratings). The flammability of building materials significantly influences the spread of fire immediately after ignition and during its development.

The standard DIN EN 13501, applicable in Germany, classifies materials into seven categories based on their flammability: A1, A2, B, C, D, E and F. Further distinctions describe the material's behaviour in fire, specifically regarding smoke development (s1, s2, s3) and flaming droplets or particles (d0, d1, d2).

In construction, wood is typically used as solid timber, glued laminated timber (glulam) or cross-laminated timber (CLT). According to the classification mentioned above, most wood-based construction materials fall under Class D-s2, d0, meaning wood is usually combustible, has a moderate smoke development rating (s2) and does not produce flaming droplets when burning (d0). The fire performance class of wood can be improved by applying appropriate fire protection measures; however, the highest achievable classification is typically B. It must, therefore, be emphasised that wood is a combustible material, meaning it can contribute to a fire load and participate in fire development if the fire is not extinguished. This fact must be considered when designing buildings with adequate fire resistance. It should be emphasised that originally, under state (*Länder*) building regulations, the use of wood as a combustible material was not permitted. The approval of combustible materials became possible only after amendments to the regulations, and this had to be done separately for each federal state.

The primary goal of fire protection is not to eliminate the possibility of fire ignition, but to control the fire in a way that allows for the safe evacuation of occupants and effective intervention by emergency services. Therefore, buildings of a particular class are assigned specific required fire resistance periods.

In Germany, according to the *Landesbauordnung* – the technical regulations that buildings and their placement must comply with – buildings are divided into five classes. This classification is based on the height of the uppermost finished floor of a room intended for human occupancy, measured relative to the average ground level (MBO, 2024). In simplified terms, buildings up to three storeys can be constructed following DIN 4102. According to this standard, building elements are designed using predefined tables, typically achieving a fire resistance rating of up to REI 30. This excludes fire separation walls, for which exceptions are usually foreseen. Buildings in Classes 4 and 5 are more challenging as they require fire resistance ratings of REI 60 and REI 90, respectively, with evacuation times reaching up to 90 min in extreme cases.

This has its justification. According to the typical fire development curve (Fig. 1), every fire follows a distinct pattern of progression. Interestingly, a self-sustaining fire tends to start extinguishing itself after approximately 90 min, which explains the basis for the fire resistance requirements in German regulations.

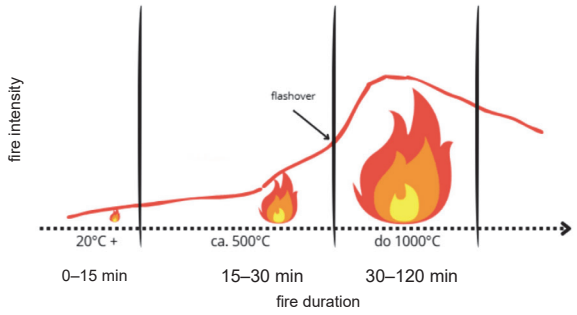


Fig. 1. Fire development diagram over time

Source: own work.

Fire safety objectives and legal framework in Germany

German regulations outline the main objectives of fire protection in buildings:

– prevent the development and spread of fire and smoke;
– enable the safe evacuation and rescue of people and animals;
– protect property;
– ensure access and effectiveness of emergency services.

To meet these goals, fire safety planning must consider factors such as fire compartment size, fire loads, evacuation routes (adapted for vulnerable users), building location and access, façade design and active fire protection systems, including alarms and sprinklers.

Ultimately, fire safety is a complex process influenced by many parameters. The choice of structural material is less important than the ability to fulfil these protection objectives; each material requires tailored strategies to achieve them.

Fire safety objectives do not exclude timber as a structural material; however, they place a responsibility on the designer to ensure that the building is planned in a way that meets fire protection goals.

RESULTS AND DISCUSSION

The MHolzBauRL: purpose and principles

The first version of *MHolzBauRL* was introduced in 2004 under the title 'Model Guideline on Fire Protection Requirements for Highly Fire-Resistant Components in Timber Construction' (*Muster-Richtlinie über brandschutztechnische Anforderungen an hochfeuerhemmende Bauteile in Holzbauweise*, M-HFHHolzR). This guideline was later replaced in 2020 by the 'Model Timber Construction Guideline' (*Muster-Holzbaurichtlinie*, MHolzBauRL). Its goal was to facilitate the construction of multi-storey timber buildings by providing explicit, standardised technical provisions that ensure fire safety compliance, especially for higher building classes requiring REI 60 and REI 90 fire resistance ratings.

Following its publication, the *MHolzBauRL* was adopted and adapted by individual German federal states (*Länder*), with varying degrees of implementation and modification reflecting regional building codes and priorities.

Several federal states have adopted the *MHolzBauRL* into their Technical Building Regulations (*Technische Baubestimmungen*), recognising the provisions of the guideline as binding and the solutions presented therein as permissible. This staggered and regionally differentiated implementation allowed for flexibility but also created a heterogeneous regulatory landscape.

The impact of introducing the *MHolzBauRL* on the German timber construction market has been significant. Since 2004, the number of multi-storey timber buildings has begun to increase, with many projects citing the guideline as essential for securing building permits and insurance. The more transparent fire safety framework has reduced planning uncertainties, accelerated approval processes and encouraged architects and developers to adopt timber in mid- and high-rise construction.

However, it is essential to identify the main challenges faced by designers who choose timber as a structural material. Unlike other building materials such as concrete and masonry, timber construction presents some unique challenges:

– As mentioned earlier, wood is a combustible material and contributes to the building's fire load;
– Timber constructions often include cavities within partitions or assemblies, which can provide pathways for fire to spread, particularly in the case of panel constructions made from solid timber and multilayer assemblies using cross-laminated timber (CLT).

Construction details by the MHolzBauRL

In response to the challenges described above, the MHolzBauRL was developed – a design guideline used in several German federal states for planning timber buildings of building Classes 4 and 5. It specifies requirements for fire resistance (REI 60 and REI 90, respectively). It provides a clear framework for the safe design of multi-storey timber structures, supporting their broader implementation in urban contexts.

The MHolzBauRL applies primarily to structures in building Classes 4 and 5, in which the load-bearing, bracing or room-enclosing structural elements are required by §26(2) Sentence 3 of the *Musterbauordnung* (MBO) to have high fire resistance (REI 60 or REI 90). The guideline allows these components, by way of exception under §26(2) Sentence 4 MBO, to be made of combustible materials such as timber.

Additionally, Section 4 of the guideline applies to walls replacing firewalls in building Class 3, as specified in §30(3) Sentence 2, No 2 MBO. It also regulates timber or timber-based external wall cladding for buildings in Classes 4 and 5, as per §28(5) Sentence 2 MBO.

Analysis of the guidelines shows that the key requirements for designing fire-safe timber architecture include:

– Using non-combustible cladding on timber structures, with the thickness of this cladding being crucial;
– Filling the structure with non-combustible materials that have a melting point above 1,000°C;
– Routing installations outside the partition area in service cavities according to MLAR and MLüAR regulations, which are beyond the scope of this study;
– Additionally, the applied claddings should be arranged in a way that hinders fire penetration into the timber structure (as demonstrated in the details in Fig. 2). Proper sealing and blocking of fire spread within the construction are also essential, and this will be further explained and illustrated with more information in the following sections.

All assemblies shown in detail are fire-resistant partitions (Fig. 2). For this reason, the structural cavities are filled with mineral wool insulation. The construction is designed so that the interior spaces are subdivided (using a colour scheme) into smaller compartments filled with non-combustible insulation with a melting point above 1,000°C. This significantly limits the potential for fire spread within the assembly. Special attention must be paid to the cladding of combustible structural elements, including proper sealing (joint treatment) and overlapping of board layers to ensure adequate protection.

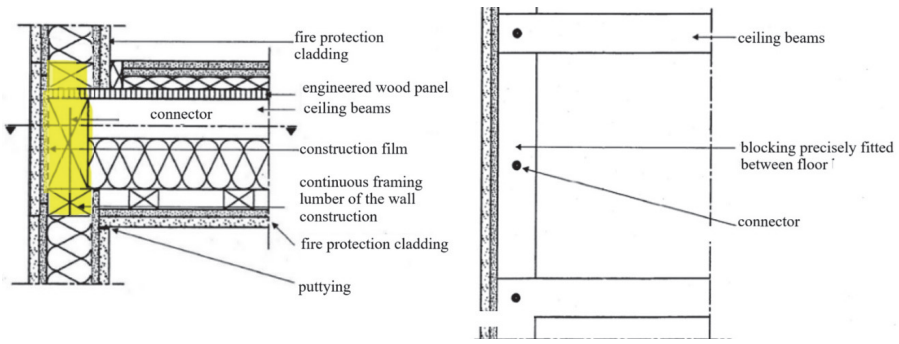


Fig. 2. Connection of ceiling to load-bearing and room-enclosing wall with fire protection cladding – e.g. stairwell or exterior wall, with the ceiling joists oriented perpendicular to the wall (left: vertical section, right: horizontal section)

Source: MHolzBauRL.

The fire-resistant wall-to-ceiling connection detail should primarily divide the partition to which the wall is attached at the junction with that wall (according to the colour coding) (Fig. 3). Next, full insulation must be provided within the wall and continuous insulation in the ceiling. The cladding should be installed with staggered joints. Attention must be paid to joint sealing as well as additional insulation in the interrupted ceiling cavity. Additionally, the non-combustible insulation layer in the floor assembly, consisting of dry screed boards, should be considered.

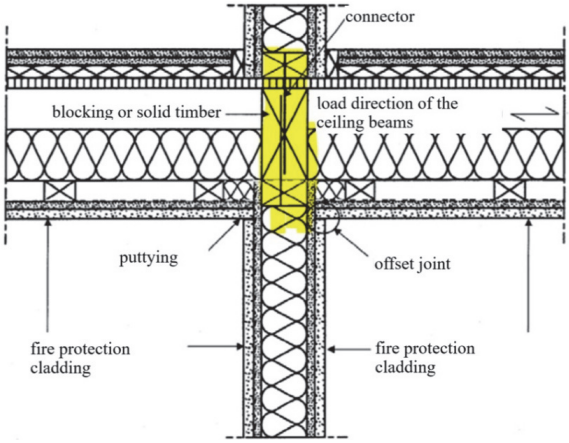


Fig. 3. Connection of load-bearing and room-enclosing wall to ceiling, with the ceiling joists oriented perpendicular to the wall (vertical section)

Source: MHolzBauRL.

The fire-resistant wall-to-ceiling connection detail should primarily divide the partition to which the wall is attached at the junction with that wall (according to the colour coding) (Fig. 4). Next, full insulation must be provided within the wall and continuous insulation in the ceiling. The cladding should be installed with staggered joints. Attention must be paid to joint sealing as well as additional insulation in the interrupted ceiling cavity. Additionally, the non-combustible insulation layer in the floor assembly, consisting of dry screed boards, should be considered.

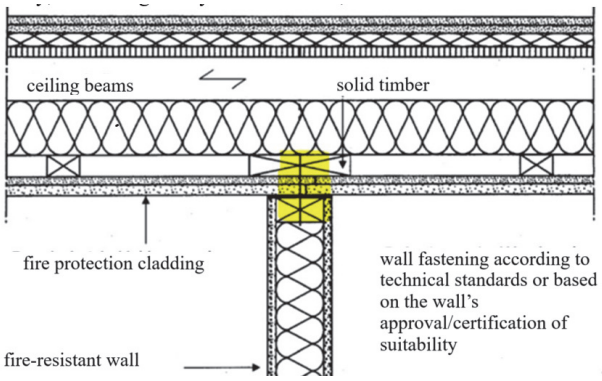


Fig. 4. Connection of load-bearing and room-enclosing wall to ceiling, with the ceiling joists oriented perpendicular to the wall (vertical section)

Source: MHolzBauRL.

In fire-resistant wall connections, it is essential to maintain the cladding layer of the building structure using an appropriate layer of boards installed with staggered joints (Fig. 5). Additionally, the cavity space within the partition must be subdivided at the junction point of the two walls.

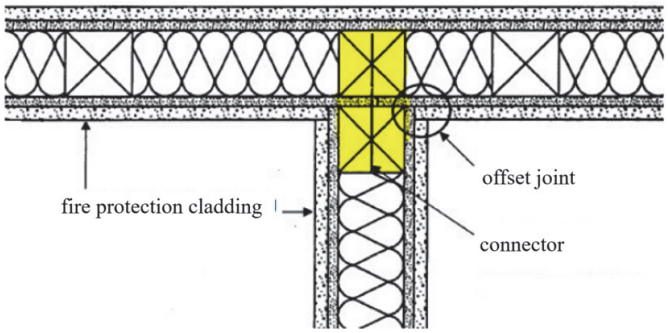


Fig. 5. Connection of a load-bearing, room-separating wall to a continuous wall with an additional stud; fire protection cladding with staggered joints (horizontal section)

Source: MHolzBauRL.

The wall connection detail can be designed in two ways while maintaining the fundamental principles set forth in the Holzbau-Richtlinie (Fig. 6). The most critical aspect remains ensuring the structure is clad with non-combustible boards of minimum required thickness, filled with appropriate insulation material and incorporating blocking of cavity spaces within the partition (marked in yellow in the colour coding). In this case, the insulation is continuous, and the junction between the perpendicular wall and the main wall is sealed with compressed insulation material.

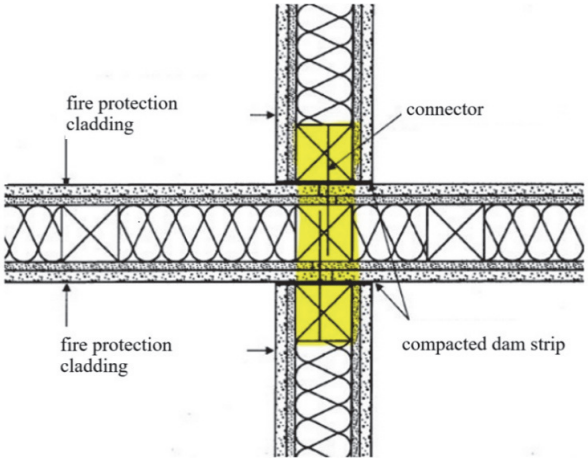


Fig. 6. Connection of load-bearing, room-separating walls to a continuous wall with an additional stud; butt joints to continuous fire protection cladding (horizontal section)

Source: MHolzBauRL.

Creating openings in walls for the installation of doors, windows or service penetrations in REI 60 and REI 90 constructions (equivalent to F60 and F90) requires internal cladding of the opening, ensuring staggered joints at corners (Fig. 7). This requirement does not apply to penetrations designed by MLAR and MLuAR regulations, which are outside the scope of this document.

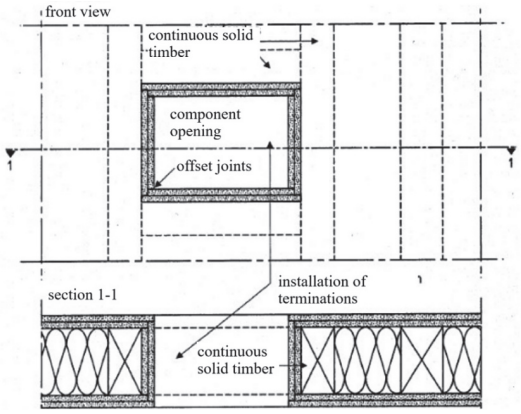


Fig. 7. Opening in the building element with fire protection cladding for the installation of doors, windows and other fittings (top image: elevation view, bottom image: horizontal section)

Source: MHolzBauRL.

Case studies: fire-resistant timber buildings in Germany (REI 90 standard)

To demonstrate the application possibilities of the MHolzBauRL, the following solutions are presented: intermediate ceilings, exterior walls and interior walls, all by the current standard DIN 4102-4. Additionally, partitions in the REI 30 standard and REI 60/90 partitions compliant with the Holzbaurichtlinie guidelines are included. It should be noted that DIN 4102-4 is used for the design of timber partitions up to a maximum REI 60 standard, with particular emphasis on partitions with REI 30 fire resistance.

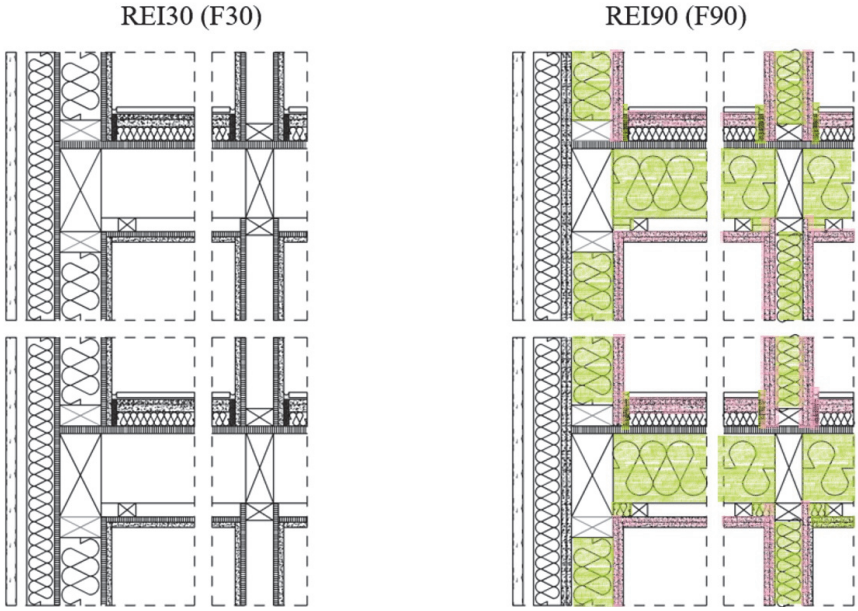


Fig. 8. Connection of the external wall to the floor/ceiling slab. Comparison of timber construction details in F30 and F90 fire resistance standards according to the MHolzBauRL

Source: own work based on DIN 4102-4 and the MHolzBauRL.

Based on the conducted case study, it can be clearly stated that the Holzbaurichtlinie, much like DIN 4102-4, provides a clear and structured set of guidelines. These define design principles and material choices for timber structures in a way that ensures compliance with fire protection objectives and formal legal requirements.

It should be noted that the main difference between the presented details lies in the modification of the cladding, which is intended to protect the structure against fire in accordance with the guidelines, ensure the continuity of the cladding, fill gaps in heterogeneous partitions and provide insulation in the partitions according to the guidelines. Corresponding changes to the structural design have been omitted in this comparison.

It should be distinguished that state (*Länder*) law is not equivalent to federal law. The so-called *Muster* regulations set a general direction and serve only as a recommendation for state-level legislation. Berlin adopted regulations allowing the use of wood as a combustible material in construction in 2018 based on an exception. In the design of such buildings, the MHolzBauRL guidelines could be used as a reference.

It should be noted that in 2018, the MHolzBauRL was not yet included in the applicable Berlin technical regulations (*Technische Baubestimmungen*) and, at that time, served only as helpful guidance, already in force in other federal states. This formal inclusion occurred only in 2025. For this reason, the authors of the study conducted a review of buildings constructed with timber structures in Classes 4 and 5 after 2018, considering the hybrid type of construction. Popular solutions to economically meet fire protection requirements were examined. The use of hybrid construction was permitted for the ground floor and circulation areas (Table 2). It is clear that such buildings are being constructed, and the changes in regulations, as well as the inclusion of the MHolzBauRL in the rules, have contributed to the emergence of timber-structured buildings in medium- and high-rise constructions in Berlin.

The overview of realised projects confirms that since the publication of the MHolzBauRL, in connection with the amendment of the MBO, the number of multi-storey timber and hybrid buildings in Berlin has grown steadily. Each of the listed facilities demonstrates how the guideline provided a transparent framework for regulatory approval. For example, the *Quartier WIR* cooperative housing complex in Weißensee (2020) shows how the guideline facilitated the planning of larger urban ensembles with multiple timber buildings under one fire safety concept. In the *Luisenblock* office and conference building (2021), the MHolzBauRL enabled the use of engineered timber in a highly visible federal project, illustrating that institutional clients were also willing to rely on timber once a codified path to compliance was available.

Residential projects such as *Walden 48* (2020) and *Mehrfamilienholzhaus Linse* (2021) reveal that private investors increasingly consider timber viable for inner-city multi-family housing once approval times are reduced and insurance premiums adjusted. Similarly, *Ausbauhaus Südkreuz* (2022) and *Stendaler Straße* (2024) demonstrate that the guideline not only supported mid- and high-rise construction in detached configurations, but also in dense infill contexts – where fire safety requirements are particularly stringent.

It is important to note that these buildings still have a hybrid character, in which the structural core is largely formed by a reinforced concrete stairwell. With the advancement of timber construction, new solutions can be expected – an example being the Walden 48 project, where elevator shafts were built from CLT panels. However, such solutions are not always necessarily the most advantageous, for instance due to structural or economic considerations.

Taken together, these examples underline that the MHolzBauRL did not introduce novel technical solutions, but rather codified accepted assemblies in a way that gave regulators, insurers and investors confidence. This translated into shorter administrative procedures – typically one-third less time compared to pre-2018 timber projects – and helped to mainstream timber as a structural option for GK4 and GK5 buildings in Berlin.

Table 2. Overview of timber or hybrid structures (allowing for reinforced concrete basements and/or ground floors as well as stairwells) commissioned between 2019 and 2024

No	Object	Location	Planner	Completion year	Structural system	Building category accord. MBO
1	Urbaner Holzbau residential building	Berlin--Adlershof	Kaden+Lager	2019	hybrid construction / / detached buildings	GK5
2	Projekt P1 residential building	Berlin--Prenzlauer Berg	Kaden Klingbeil Architekten / / Kaden _Lager	2019	hybrid construction / / detached building	GK5
3	Quartier WIR residential estate	Berlin--Weissensee	Deimel Oelschläger Architekten	2020	hybrid construction / / detached buildings	GK5
4	Luisenblock Deutscher Bundestag, office and conference building	Berlin--Mitte	Sauerbruch Hutton in coorporation with Kaufmann Bausysteme	2021	hybrid construction / / detached building	GK5
5	Walden 48 residential building	Berlin--Friedrichshain	Scharabi	2020	hybrid construction / / detached building	GK5
6	Mehrfamilienholzhaus Linse building – residential with supporting facilities	Berlin--Schöneberg	Scharabi Architekten / / Praeger Richter Architekten	2021	hybrid construction / / infill building	GK5
7	Kudamm 210 hotel extension	Berlin--Charlottenburg	JWA + Ralf Wilkening Architect	2022	hybrid construction / / infill building	GK5
8	Ausbauhaus Südkreuz residential building	Berlin--Schöneberg	Praeger Richter Architekten	2022	hybrid construction / / detached building	GK5
9	Stendaler Straße residential with supporting facilities	Berlin--Moabit	AHM Architekten	2024	hybrid construction / / detached building	GK5
10	Haus im Park nursing home	Berlin--Pankow	Modersohn & Freiesleben Architekten Partnerschaft	2024	hybrid construction / / detached building	GK4

Source: own work.

CONCLUSIONS

This study aimed to determine whether the MHolzBauRL provides a robust, practical and scalable framework for the fire-safe realisation of multi-storey timber buildings in Germany. The doctrinal review, comparison with DIN 4102-4 and analysis of built projects demonstrate that the guideline effectively translates the generic REI 60/90 requirements of the *Musterbauordnung* into a coherent design logic that can be implemented without requiring full-scale fire tests. Its prescriptive hierarchy – non-combustible claddings, cavity compartmentation and controlled service routing – effectively bridges the long-standing regulatory gap between low-rise timber prescriptions and the performance-based approvals required for taller structures.

Projects completed since 2015 indicate that citing the MHolzBauRL in the fire safety concept typically shortens permitting procedures and could remove the insurance surcharges that burdened earlier timber developments,

suggesting that legal clarity rather than technical novelty is now the primary driver of investor confidence. Yet, the guideline's voluntary, state-by-state adoption has produced a patchwork of editions and effective dates that complicate cross-regional procurement and hinder consistent performance monitoring. Federal consolidation – ideally through incorporation into the forthcoming DIN EN 1995-1-2/NA – would amplify the MHolzBauRL's impact and facilitate systematic data collection. A similar process could be implemented in Poland, provided that combustible load-bearing elements in medium- and high-rise buildings are clearly identified, a nationally agreed catalogue of prefabricated assemblies is created and mechanisms for updating the catalogue are established as testing methods and products evolve. Two research needs remain pressing: long-term monitoring of in-service fire incidents to verify assumptions about charring and compartment integrity, as well as integrating life-cycle carbon metrics into fire safety decision-making to balance climate and safety objectives transparently. Overall, the MHolzBauRL demonstrates that concise, assembly-based fire regulations can coexist with innovation and decarbonisation goals when they are embedded in a clear approval pathway; consolidating the guideline at federal level and encouraging its adaptation in neighbouring countries would be decisive steps towards mainstreaming tall timber construction across Europe.

Authors' contributions

Conceptualisation: K.K. and A.S.; methodology: K.K. and A.S.; validation: A.S.; formal analysis: K.K. and A.S.; investigation: K.K.; data curation: K.K.; writing – original draft preparation: K.K.; writing – review and editing: K.K. and A.S.; visualisation: K.K.; supervision: A.S.; project administration: A.S.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Bauministerkonferenz (2020). *Model guideline on fire-safety requirements for highly fire-resistant timber components (M-HFHHolzR 2020).*

Bauministerkonferenz (2021). *Model guideline on fire-safety requirements for ventilation systems (M-LüAR).*

Bauministerkonferenz (2024a). *Model Building Code (Musterbauordnung – MBO).*

Bauministerkonferenz (2024b). *Model guideline on fire-safety requirements for service installations (MLAR).*

Buchanan, A. H. & Abu, A. K. (2016). *Structural Design for Fire Safety*. Wiley. https://doi.org/10.1002/9781118700402

Churkina, G., Organschi, A., Reyer, C. P. O., Ruff, A., Vinke, K., Liu, Z., Reck, B. K., Graedel, T. E. & Schellnhuber, H. J. (2020). Buildings as a global carbon sink. *Nature Sustainability*, *3* (4), 269–276. https://doi.org/10.1038/s41893-019-0462-4

Deutsches Institut für Normung [DIN]. (2016). *Fire behaviour of building materials and building components. Part 4. Synopsis and application of classified building materials, components and special components* (DIN 4102-4:2016-05) [English version]. Beuth Verlag.

Deutsches Institut für Normung [DIN]. (2019). *Fire classification of construction products and building elements. Part 1. Classification using data from reaction-to-fire tests* (DIN EN 13501-1:2019-12) [English version]. Beuth Verlag.

Gustavsson, L. & Sathre, R. (2011). Energy and CO_2 analysis of wood substitution in construction. *Climatic Change*, *105* (1–2), 129–153. https://doi.org/10.1007/s10584-010-9876-8

Hofmeister, S. (2022). *Timber buildings: S, M, L*. Detail.

Hopkin, D., Węgrzyński, W., Gorska, C., Spearpoint, M., Bielawski, J., Krenn, H., Sleik, T., Blondeau, R. & Stapf, G. (2024). Full-Scale Fire Experiments on Cross-Laminated Timber Residential Enclosures Featuring Different Lining Protection Configurations. *Fire Technology*, *60* (6), 3771–3803. https://doi.org/10.1007/s10694-024-01581-1

Huß, W., Kaufmann, M. & Merz, K. (2019). *Building in timber: Room modules*. Detail.

Kaufmann, H., Krötsch, S. & Winter, S. (2024). *Atlas: Multi-storey timber construction – Fundamentals, construction, case studies*. Detail.

Lennartz, M. W. & Jacob-Freitag, S. (2015). *Neues Bauen mit Holz* [New building with wood]. Birkhäuser.

Li, L., Lei, Y., Wu, S., Chen, J. & Yan, D. (2017). The health economic loss of fine particulate matter ($PM_{2.5}$) in Beijing. *Journal of Cleaner Production*, *161*, 1153–1161. https://doi.org/10.1016/j.jclepro.2017.05.029

Ljunggren, F., Fredriksson, M., Johansson, N. & Sasic Kalagasidis, A. (2025). Cross-laminated timber: a state-of-the-art review of moisture, fire, acoustics, and energy-related aspects. *Wood Material Science & Engineering*, 1–23. https://doi.org/10.1080/17480272.2025.2507145

O'Hegarty, R., Kinnane, O., Newell, J. & West, R. (2021). High performance, low carbon concrete for building cladding applications. *Journal of Building Engineering*, *43*, 102566. https://doi.org/10.1016/j.jobe.2021.102566

Perković, N., Rajčić, V. & Barbalić, J. (2024). Fire Resilience of Load-Bearing Wall Made of Hollow Timber Elements. *Fire*, *7* (12), 433. https://doi.org/10.3390/fire7120433

Zang, X., Liu, W., Wu, D., Pan, X., Zhang, W., Bian, H. & Shen, R. (2023). Contemporary Fire Safety Engineering in Timber Structures: Challenges and Solutions. *Fire*, *7* (1), 2. https://doi.org/10.3390/fire7010002

MUSTERHOLZBAURICHTLINIE (MHOLZBAURL) JAKO NARZĘDZIE KSZTAŁTOWANIA WIELOKONDYGNACYJNYCH BUDYNKÓW DREWNIANYCH W NIEMCZECH

STRESZCZENIE

Wobec rosnących wymagań klimatycznych drewno ponownie zyskuje rangę niskoemisyjnego materiału konstrukcyjnego do wykorzystania w budownictwie obiektów średnio- i wielokondygnacyjnych, lecz jego podatność na zapalenie wciąż ogranicza zastosowanie. Artykuł poddaje krytycznej analizie MHolzBauRL – wytyczne wdrożone w wybranych krajach związkowych Niemiec – jako zintegrowane narzędzie prawno-techniczne umożliwiające projektowanie wielokondygnacyjnych konstrukcji drewnianych w klasach odporności ogniowej REI 60 i REI 90. W artykule omówiono zakres i hierarchię regulacji, zasady detalowania (niepalne okładziny, przegrody pożarowe, prowadzenie instalacji) oraz porównano je z niemiecką normą DIN 4102-4. Dzięki studium zrealizowanych obiektów budowlanych potwierdzono, że przyjęcie wytycznych skraca procedury administracyjne i zwiększa zaufanie inwestorów do konstrukcji z drewna inżynierskiego. Wnioskujemy, że MHolzBauRL dostarcza spójnych, jednoznacznych kryteriów bezpiecznego wznoszenia budynków drewnianych o dużej liczbie kondygnacji, a ponadto identyfikujemy potrzebę szerszej harmonizacji przepisów, w tym potencjalnego wdrożenia analogicznych rozwiązań w Polsce.

Słowa kluczowe: MHolzBauRL, budownictwo drewniane, bezpieczeństwo pożarowe, budynki wielokondygnacyjne

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DETERMINATION OF THE D_{50} PARTICLE DIAMETER IN NON-COHESIVE SOILS BASED ON DILATOMETER TESTS

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ABSTRACT

The increasing demands placed on geotechnics require the development of interpretation methods to obtain as many geotechnical parameters as possible from a single test profile. Extensive databases of documented test points were used to construct and develop a direct correlation between the measured pressures p_0 and p_1 from the dilatometer tests (DMT) and the laboratory results of grain size distribution tests of cohesionless soils from the analysed boreholes, as well as the pore water pressure (u_0). Furthermore, the analysis considered pore water pressure (u_0). The primary achievement of this paper is the development of an original correlation that enables the direct estimation of the equivalent diameter (D_{50}) of cohesionless soils based on DMT results. Furthermore, the D_{50} values calculated from the proposed relationship were validated using laboratory test results from soils from other sites not included in the analysis during the development of the proposed empirical relationship.

Keywords: in situ test, mineral soil, sand grain size

INTRODUCTION

When designing an engineering structure, many factors should be considered, including safety considerations, without which it is impossible to carry out even the most ambitious plan. The engineer's task is to gather various types of data to verify whether the soil is suitable for the designed building, allowing for the construction of solid foundations. Soil type and geotechnical parameters needed for designing are obtained from soil tests (Schneider et al., 1997; Orr, 2000; Młynarek, 2007; Bond & Harris, 2008; Wierzbicki, 2010; Młynarek, Stefaniak & Wierzbicki, 2012; Zabielska-Adamska, 2019; Tarnawski Ed., 2020; Zabielska-Adamska, 2020; Rasti, Adarmanabadi, Pineda & Reinikainen, 2021). Soil investigations are thus indispensable here. They can be subdivided into field and laboratory tests. Laboratory tests have several advantages, including accuracy, a well-defined stress state, and the ability to control drainage conditions (Gryczmański, 1995; Pisarczyk, 2014; Cichy, Lechowicz & Garbulewski, 2017). In situ tests, the subject of this article, are used to test soil parameters directly in the field. Based on them, it is possible to determine the geotechnical parameters of soils in their natural state. The most common in situ soundings include the cone penetration test (CPT) and the Marchetti dilatometer test (DMT) (Schmertmann, 1978; Marchetti, 1980; Lunne, Robertson & Powell, 1997; Mayne, Martin & Schneider, 1999; Fellenius & Eslami, 2000; Młynarek, Gogolik & Marchetti, 2006; Młynarek, 2007; Bałachowski & Kurek, 2008; Godlewski & Wszędyrówny-Nast, 2016; Hakam, Febriansyah & Adji, 2020;

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Nepelski, 2020; Tankiewicz & Bagińska, 2021; Robertson & Cabal, 2022; Mayne, Greig & Cargille, 2024; Mayne, Cargille & Greig, 2025). They are also often used to supplement borehole data.

Despite significant differences in test methodology, CPT and DMT soundings are considered equivalent. For example, in Poland, research with the application of CPT and DMT probes is carried out in the following centres: Department of Engineering Geology and Geotechnics at University of Life Sciences in Poznań (Młynarek et al., 2006), Department of Geotechnics, Geology and Marine Civil Engineering at Gdańsk University of Technology (Bałachowski, 2006), Institute of Hydrogeology and Applied Geology at University of Warsaw (Kaczyński, 2017), Department of Geotechnics and Foundation at the Building Research Institute in Warsaw (Wysokiński, 2007), Department of Geotechnical Engineering at Warsaw University of Life Sciences – SGGW (Rabarijoely, 2000; Lechowicz & Rabarijoely, 2005), Institute of Geology, Faculty of Geographical and Geological Sciences at Adam Mickiewicz University in Poznań (Wierzbicki, 2010), Faculty of Civil Engineering at Cracow University of Technology (Truty & Podleś, 2018), Faculty of Civil and Environmental Engineering at University of Zielona Góra (Szajna, 2015; Szajna & Gontaszewska, 2015) and Faculty of Civil Engineering and Architecture at Lublin University of Technology (Nepelski, 2020).

The article does not describe the DMT and CPT methodologies, as this information can be found in the journal archives (Bajda, Skutnik, Lech & Rabarijoely, 2018; Rabarijoely, 2018; Rabarijoely, 2019a; Rabarijoely, 2019b). We focus here on the analysis of the accuracy of the subsoil layer identification methods and their comparison with samples taken for laboratory tests. The research was conducted on the Stegny site and the campus grounds of Warsaw University of Life Sciences – SGGW (hereinafter referred to as "the WULS-SGGW campus"). This publication aims to develop a relationship for determining the grain size (D_{50}) for sand using DMT results from both sites.

LITERATURE REVIEW

Cone penetration and the Marchetti dilatometer testing methods in geotechnical engineering

CPT and DMT tests are commonly used to identify geotechnical conditions in all engineering structures. At the same time, the cone penetration test with pore pressure measurements (SCPTu) and the seismic dilatometer test (SDMT) are also used for buildings classified in the third geotechnical category. Due to earlier practical introductions and more extensive interpretation rules, CPT and later CPTu tests were initially considered more reliable for assessing geotechnical conditions for the proposed building. Despite significant differences in test methodology, CPT and DMT tests complement each other.

When presenting Marchetti's dilatometer, an innovative research device, the soil subdivision was based on the material index (Marchetti, 1980; Cruze, 2009; Cruz, 2010; Table 1).

Table 1. Soil classification based on the material index

Soil type		Material index (I_D) [-]
Peat or sensitive clays	peat / sensitive clays	< 0.10
	clay	0.10–0.35
	silty clay	0.35–0.60
	clayey silt	0.60–0.90
	silt	0.90–1.20
	sandy silt	1.20–1.80
Non-cohesive soils	silty sand	1.80–3.30
	sand	> 3.30

Source: Marchetti (1980).

MATERIAL AND METHODS

The Stegny site and the WULS-SGGW campus site are located on a post-glacial plateau. It is a flat area located in the Mazovian basin, developed during the Neogene (Fig. 1). According to archival data, the basin bottom is composed of marls, siliceous limestones, and gaize. The thickness of Paleogene and Neogene deposits exceeds 200 m. The upper part of the Neogene is represented by Pliocene sediments, which consist mainly of motley clays with lenses and layers of sand and silt with a thickness of about 105 m. The erosive activity of waters in the periglacial and later periods, coupled with glaciotectonic deformation, resulted in a differentiated surface of Pliocene clays. Quaternary sediments with a thickness of 26–49 m occur above the clay layers. These deposits were formed through the accumulation of glacial, fluvioglacial, and fluvial sediments. At the base of the Quaternary, ice-dammed clay-silt deposits with silt interbeds occur (Morawski, 1984; Barański et al., 2004).



Fig. 1. Map of Warsaw (scale 1 : 20 000) with the location of the study sites

Source: own work.

Material

This paper presents the test results for mineral subsoils obtained from the Stegny site and the WULS-SGGW campus in Warsaw, where the Department of Geotechnical Engineering carried out a laboratory and field-testing program (Lechowicz & Rabarijoely, 1996; Truty & Podleś, 2018). The grain-size distribution curve obtained from laboratory tests for mineral soils from the described sites is presented in Figure 2. The index properties of mineral soils in the Stegny site and the WULS-SGGW campus test site are presented in Table 2. Figure 3 presents the diagram chart proposed by Marchetti and Crapps for the analysed sites (Marchetti & Crapps, 1981).

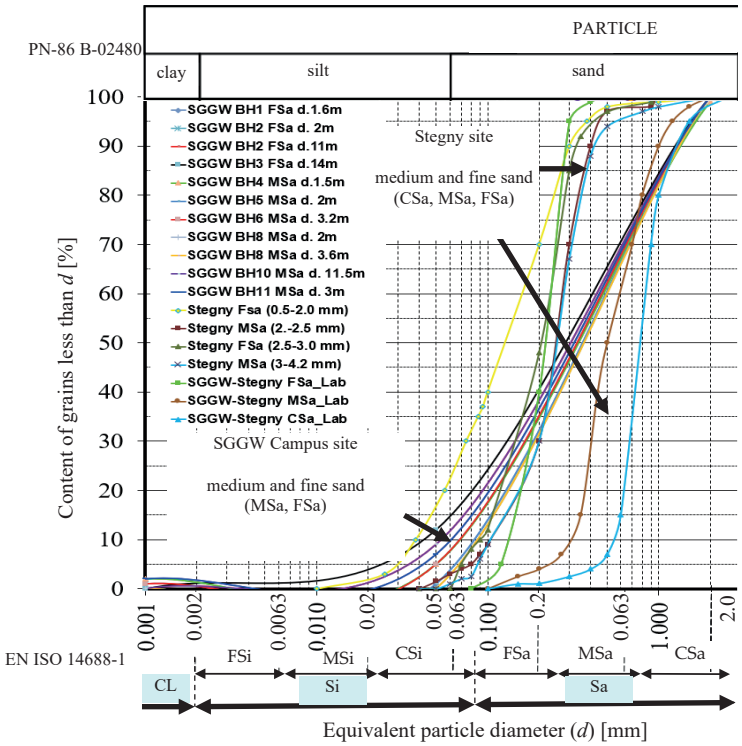


Fig. 2. Grain-size distribution curve obtained from laboratory tests for the mineral soils from the described sites

Source: own work.

Table 2. Index properties of mineral subsoils from the Stegny site and the WULS-SGGW campus test site

Site	Type of soil	Organic content (I_{om}) [%]	Calcium carbonate content [%]	Water content (w_n) [%]	Liquid limit (w_L) [%]	Density	
						Unit weight of soil (ρ) [t·m^{-3}]	Specific weight of soil (ρ_s) [t·m^{-3}]
Stegny	fine and medium sand (FSa, MSa)	0	< 1	5.4	–	1.7	2.68–2.66
WULS-SGGW campus	fine and medium sand (FSa, MSa)	0	1–3	6.7	–	1.85	2.68–2.66

Source: own work.

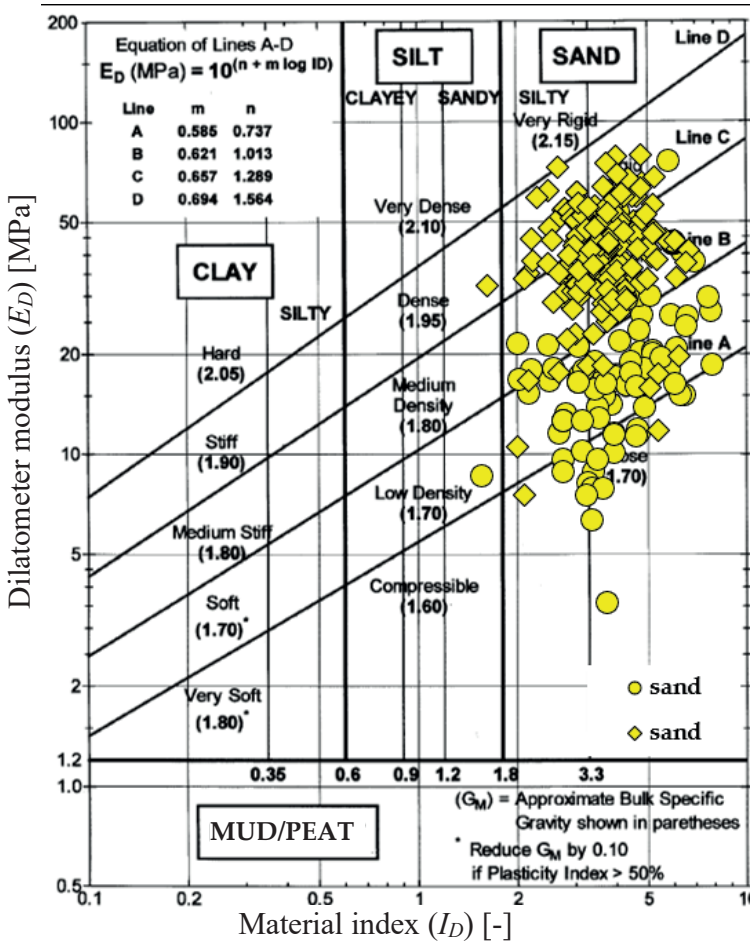


Fig. 3. Chart for estimating the unit weight (normalised to γ_w) of sands from the Stegny site and the WULS-SGGW campus test site

Source: own work based on Marchetti and Crapps (1981).

TEST RESULTS

At the Stegny site and the WULS-SGGW campus site, DMT tests were performed by the Department of Geotechnical Engineering at Warsaw University of Life Sciences – SGGW. The WULS-SGGW campus test site was in the subsoil underneath one of the buildings. The DMT soundings on the WULS-SGGW campus were performed for the future Building 34 and Building 37 (Fig. 4). The measured parameters were the pressures (p_0 and p_1), which, after conditioning, were registered by the device as pressures A and B, respectively (Fig. 4). Based on these measurements, the dilatometer indexes (3), (4), (5) were calculated and presented in Figure 5. The profiles of the material index (I_D), the horizontal stress index (K_D), and the dilatometer modulus (E_D) from the DMT for selected layers for non-cohesive soils of these two sites are shown in Figure 5. The groundwater levels are located at: (a) Stegny site – depth 3.2 m; *OCR* = 2.5–3.5; (b) WULS-SGGW campus site – depth 10.0 m; *OCR* = 3–7.

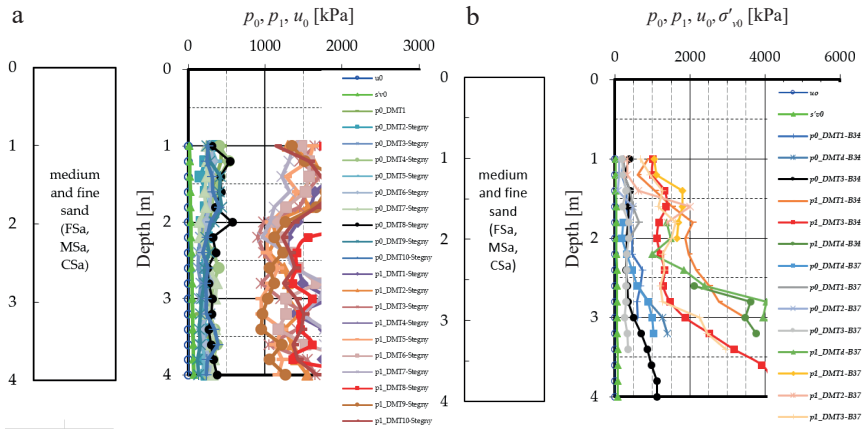


Fig. 4. Profiles of p_0 and p_1 from dilatometer tests (DMT tests, hydrostatic pressure u_0 and vertical effective stress σ'_{v0} for the Stegny site (a) and the WULS-SGGW campus site (b)

Source: Lechowicz, Rabarijoely and Szczypiński (2004), Lechowicz, Fukue, Rabarijoely and Sulewska (2018).

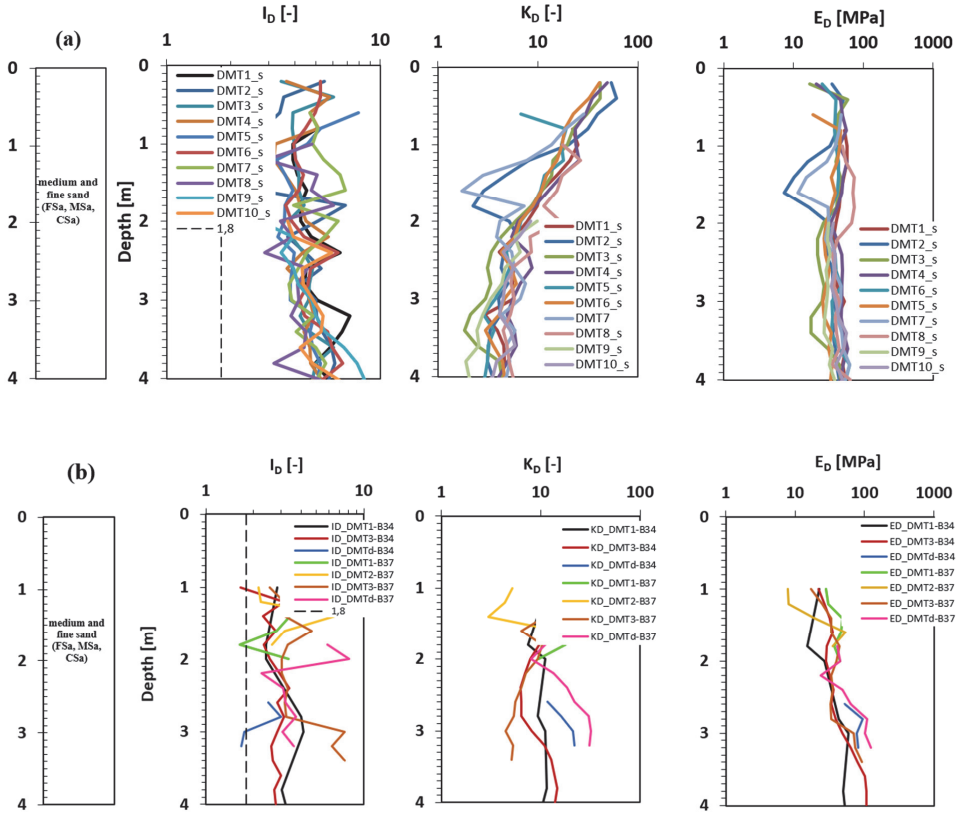


Fig. 5. Profiles of I_D, K_D, and E_D from DMT tests for the Stegny site (a) and the WULS-SGGW campus site (b) (B-34 – Building 34, B-37 – Building 37)

Source: Lechowicz et al. (2004), Lechowicz et al. (2018).

Estimation theory

A literature review reveals that the physical process in CPTu is governed by the law that describes the cone's displacement within the soil medium. It is equivalent to displacing a material point in a medium exhibiting friction (Banach, 1950; Młynarek & Sanglerat, 1983; Młynarek, 2007).

A similar mechanism also occurs in the subsoil during DMT tests. The form of the function describing DMT testing in 2008 was revealed by the research team of Professor Młynarek (Młynarek et al., 2008). Since dilatometer testing is strength and stationary testing, in which deformations of subsoil are connected with the rate pressures applied at the dilatometer tip, the equation describing this process may be written as: $F_2(P_d, V_d, \Theta_1, \Theta_2) = 0$ [where P_d – measured process parameter, e.g. pressure p_0, p_1 or $(p_0 - p_1)$, V_d – the rate at which pressure is applied onto the membrane of the dilatometer vane]. Parameter Θ_1 is recorded by the key $\Theta_1 = f(X_1, \ldots, X_9)$ [where: X_1 – effective unit weight of soil, X_2 – moisture content, X_3 – percent of organic matter, X_4 – degree of decay, X_5 – content of calcium carbonate ($CaCO_3$), X_6 – percent of clay, silt or sand fraction, X_7 – modulus of deformation of organic matter, X_8 – parameter describing shear strength, cohesion, angle of internal friction, X_9 – structure of organic soil]. Parameter Θ_2 contains the functions: $\Theta_1 = f(X_1^d, X_2^d, X_3^d)$ [where: X_1^d – variable describing the membrane geometry, e.g. diameter, X_2^d – membrane stiffness, X_3^d – membrane roughness] (Młynarek et al., 2008).

For determining parameter D_{50} based on DMT tests, parameters p_0 and p_1, as well as u_0 and σ'_{v0} were taken into account in the statistical analysis. These quantities can be treated as random variables. 17 DMT tests (including 10 DMT tests from the Stegny site and 7 DMT tests from the WULS-SGGW campus site) from the sand layer were used, with a count of 12–17 measurements (depth profiles), with 264 data points. The distribution of the tested random variables was checked. In the case of most studies, i.e. random samples in a statistical sense, there was no reason to reject the hypothesis of normality (Shapiro–Wilk tests suitable for small samples were applied; they are available, e.g. in the Statgraphics statistical software package). No other distribution was found to which the tested quantities complied (Bleistein & Handelsman, 1986).

Estimation of soil grain size (D_{50})

The aim of developing new formulas for calculating the grain size (D_{50}) of sands is to derive relations closely related to the dilatometer test, namely, the dilatometer indexes. The three main indexes obtained from a dilatometer test are: the material index (I_D), the horizontal stress index (K_D), and the dilatometer modulus (E_D). Apart from the parameters of the DMT dilatometer tests, the results of sieve tests were also used to determine the particle size distribution of sands. Several stages were employed to determine the authors' dependencies in calculating the grain size (D_{50}) of sands, which varied according to the given parameters due to different data for specific sites. The Solver module was used to determine the grain size (D_{50}) of sands based on the dependence of DMT results, which consisted of performing all the calculations carried out in this study. This function is often used for linear programming, including modelling and optimising any decision problems. This linear programming should be based on creating a reality model in which the objective function is a key element, the value of which is subordinate to a specific profitability criterion (max/min). The solution of the function is assisted by using variable coefficients (the a and b factors were assumed for the grain size D_{50} of sands determined in this paper), due to which maximum or minimum values are achieved.

Observation of the obtained results shows that there is a strong relationship between parameter D_{50} and dilatometer pressures, i.e. p_0 and p_1, as well as u_o and σ'_{v0}: $D_{50} = f(p_0, p_1, u_0, \sigma'_{v0})$. A formula was proposed for non-cohesive soils at the studied sites based on this criterion, and the lowest value of the mean square relative deviation was calculated. The formula that was used for the calculations is our original proposal. The summarised test results, i.e. I_D, K_D, and E_D values from DMT and u_0 tests, allowed us to determine the formula for the grain size (D_{50}) of sands in the following form:

$$D_{50} = f\left(a, b, p_0, p_1, u_0, \sigma'_{v0}\right), \tag{1}$$

where:
a, b – factors.

The formula was made dependent on the variables p_0, p_1, u_0, and σ'_{v0}, which belong to variable cells in the Solver function. An additional column has been added to determine the percentage deviation between the calculated D_{50} result for a given depth and the value obtained from laboratory tests. The calculations were focused on obtaining the lowest possible mean square relative deviation (*MSRD*). The values for the statistical compilation were calculated from the following formulas:

– maximal relative deviation:

$$MRD \max_{i=1,2,\ldots,m} = \left|\frac{y_i - \bar{y}_i}{y_i}\right| \cdot 100\%, \tag{2}$$

– mean square relative deviation:

$$MSRD = \left[\sqrt{\frac{1}{m}\sum_{i=1}^{m}\left(\frac{y_i - \bar{y}_i}{y_i}\right)^2}\right] \cdot 100\%. \tag{3}$$

The function was programmed to achieve the lowest possible target cell value. The results of the calculations are presented further in the text. For non-cohesive soils located in the study area, i.e. in the Stegny site and the WULS-SGGW campus site, and the data obtained from the dilatometer test, a formula was proposed, and the grain size (D_{50}) of sands was calculated.

From a physical standpoint, it is possible to determine the D_{50} value based on DMT tests, which makes it dependent on the I_D. The final form of the formula for determining the D_{50} value based on the DMT tests can be presented as follows. Using the Solver module, the values of the factors a and b for which there is the lowest value of the mean square relative deviation for the material index were determined. For the proposed formula for D_{50}, the following statistical values were obtained (summarised in Figure 6). The obtained pattern is as follows:

$$D_{50\,DMT \approx SDMT} = a \cdot e^{-\frac{b}{I_D}}\ [\text{mm}], \tag{4}$$

where:
a = 0.80,
b = 2.00,
I_D – material index [-],
e – Euler's or Neper's number (e = 2.72) [-].

The values obtained from the laboratory test are related to the values calculated based on Formula 4. The deviation values obtained during the calculations were acceptable, with the following results: MSRD of 13.5% and MRD of 26.0%. The correlation between the values calculated (from Formula 4) and measured is presented in Figure 6.

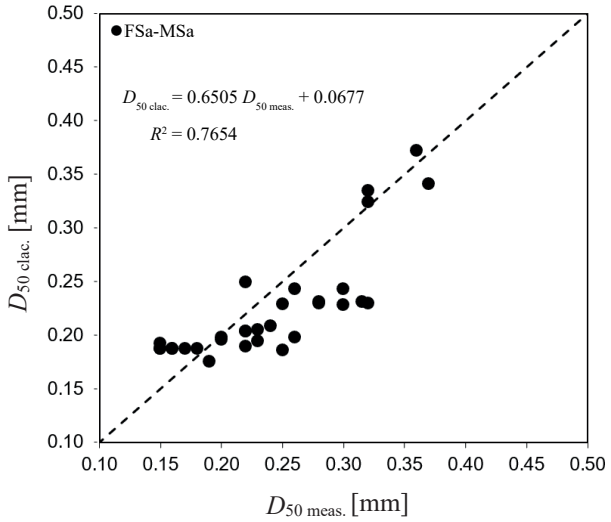


Fig. 6. Summary of the values of the soil grain size (D_{50}) obtained from laboratory tests and calculated using Formula 4 based on DMT results from the analysed Stegny site and the WULS-SGGW campus site

Source: own work.

The values calculated using the new formula align well with those obtained from laboratory tests. They behave predictably and fit into an overall trend line, while the laboratory test values have higher amplitudes. The relationship between the results obtained from laboratory tests and those determined based on Formula 4 was previously presented.

Knowledge about the mechanical strength related to D_{50} values can be used for model tests of the load-bearing capacity of surfaces made of soil mixtures, and may indirectly contribute to minimising the scope and shortening the time of laboratory and field tests. Additionally, the D_{50} value in the subsoil affects the value of the filtration coefficient, not only under the planned building.

CONCLUSIONS

Marchetti's dilatometer tests enable the measurement of soil parameters with almost continuous accuracy. They require specialised equipment and offer fast and easy testing under in situ conditions, and therefore, are very useful in obtaining soil data. The results are generally reproducible, enabling the calculation of important soil parameters used in construction and environmental engineering. To increase the reliability of the results, laboratory analysis of the soil samples should be applied. The obtained values of D_{50} for soils using the proposed new formula are comparable to those obtained directly after probing with another device or through calculation methods. The proposed formula is both convenient and user-friendly, making it very helpful for both students and designers. Despite the large dataset used in the statistical analysis, the proposed relationship should be used with caution in specific ground conditions, e.g. highly overconsolidated or cemented soils.

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Authors' contributions

Conceptualisation: S.R., M.L. and M.B.; methodology: S.R., M.B. and K.M.L.; validation: S.R. and M.B.; formal analysis: S.R., M.L. and M.B.; investigation: S.R., M.L. and M.B.; data curation: S.R., M.B. and K.M.L.; writing – original draft preparation: S.R. and M.L.; writing – review and editing: S.R. and M.L.; visualisation: S.R.; supervision: M.L. and K.M.L.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Bajda, M., Skutnik, Z., Lech, M. & Rabarijoely, S. (2018). Ocena parametrów gruntów organicznych do projektowania wzmocnienia podłoża drogi ekspresowej na podstawie badań *in situ*. *Acta Scientiarum Polonorum. Architectura*, *17* (2), 107–114. https://doi.org/10.22630/ASPA.2018.17.2.19

Bałachowski, L. & Kurek, N. (2008). Influence of boundary conditions in calibration chamber. *Archives of Civil Engineering*, *54* (4), 653–668.

Banach, S. (1950). *Mechanika* (Vols 1, 2). Warszawa: Czytelnik.

Barański, M., Kaczyński, R., Borowczyk, M., Kraużlis, K., Trzciński, J., Wójcik, E., Granacki, T., Szczepański & Zawrzykraj, P. (2004). *Ocena zachowania się iłów plioceńskich ze Stegien w warunkach naprężeń efektywnych* (projekt badawczy KBN, 5, T12B) [unpublished].

Bleistein, N. & Handelsman, R. A. (1975). *Asymptotic expansions of integrals*. New York: Dover Publications.

Bond, A. & Harris, A. (2008). *Decoding Eurocode 7*. London: CRC Press.

Cichy, W., Lechowicz, Z. & Garbulewski, K. (2017). Naprawy i wzmocnienia konstrukcji budowlanych. In *Geotechnika: XXII Ogólnopolskie Warsztaty Pracy Projektanta Konstrukcji, Wisła, 7–10 marca 2017 r. Wykłady* (Vol. 1, pp. 21–32). Kraków: Polski Związek Inżynierów i Techników Budownictwa. Oddział Małopolski.

Cruze, I. R. (2009). *An evaluation of seismic flat dilatometer and lateral stress seismic piezocone*. Vancouver: The University of British Columbia.

Fellenius, B. H. & Eslami, A. (2000). Soil profile interpreted from CPTu data. In *Proceedings of GEOTECH –Year 2000. Developments in Geotechnical Engineering* (Vol. 1, pp. 163–171). Bangkok: Asian Institute of Technology.

Fragaszy, R. J., Su, W. & Siddiqi, F. H. (1990). Effects of oversize particles on the density of clean granular soils. *Geotechnical Testing Journal*, *13* (2), 106–114. https://doi.org/10.1520/GTJ10701J

Godlewski, T. & Wszędyrówny-Nast, M. (2016). Correlations of regional geotechnical parameters on the basis of CPTU and DMT tests. In *Proceedings of 13th Baltic Sea Geotechnical Conference* (pp. 22–27). Vilnius: Vilnius Gediminas Technical University Press.

Gryczmański, M. (1995). *Wprowadzenie do opisu sprężysto-plastycznych modeli gruntu*. Warszawa: Komitet Inżynierii Lądowej i Wodnej PAN.

Hakam, A., Febriansyah, D. & Adji, B. M. (2020). Liquefaction Mapping Procedure Development: Density and Mean Grain Size Formulations. *Geomate Journal*, *18* (70), 155–161.

Kaczyński, R. R. (2017). *Warunki geologiczno-inżynierskie na obszarze Polski*. Warszawa: Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy.

Lechowicz, Z., Fukue, M., Rabarijoely, S. & Sulewska, M. J. (2018). Evaluation of the Undrained Shear Strength of Organic Soils from a Dilatometer Test Using Artificial Neural Networks. *Applied Sciences*, *8* (8), 1395. https://doi.org/10.3390/app8081395

Lechowicz, Z. & Rabarijoely, S. (1996). Wykorzystanie badań in situ w ocenie wzmocnienia słabonośnego podłoża zapory budowanej etapowo. In *Materiały VII Konferencji Technicznej Kontroli Zapór, Rytro* (pp. 231–240). Warszawa: Instytut Meteorologii i Gospodarki Wodnej.

Lechowicz, Z. & Rabarijoely, S. (2005). Evaluation of organic subsoil conditions after large deformations. In *Proceedings of the 2nd International Conference on Problematic Soils, Petaling Jaya, Malaysia* (Vol. 3, pp. 1075–1082). Singapore: CI-Premier.

Lechowicz, Z., Rabarijoely, S. & Szczypiński, P. (2004). Wykorzystanie badań dylatometrycznych do określenia rodzaju i stanu gruntów organicznych [The use of dilatometer test to determine the type and state of organic soils]. *Przegląd Naukowy. Inżynieria i Kształtowanie Środowiska*, *2* (29), 191–201.

Lunne, T., Robertson, P. K. & Powell, J. J. M. (1997). *Cone Penetration Testing in Geotechnical Practice*. London: Blackie Academic/Chapman-Hall Publishers.

Marchetti, S. (1980). In Situ Tests by Flat Dilatometer. *Journal of the Geotechnical Engineering Division*, *106* (GT3), 299–321.

Marchetti, S. & Crapps, D. K. (1981). *Flat dilatometer manual* (internal report). Gainesville, FL: GPE.

Mayne, P. W. (2006). Interrelationships of DMT and CPT readings in soft clays. In *Proceedings of the 2nd International Conference on Flat Dilatometer Testing, Washington, D.C.* (pp. 231–236). Lancaster: In-Situ Soil Testing.

Mayne, P. W., Cargill, E. & Greig, J. (2025). Piezocone Screening Approach for Regular, Organic, and Sensitive Soft Clays. In *Geotechnical Frontiers 2025* (pp. 22–37). Reston, VA: American Society of Civil Engineers.

Mayne, P. W., Greig, J. & Cargill, E. (2024). Application of two analytical CPTU solutions to sensitive clay in Québec. In *Proceedings of the 7th International Conference on Geotechnical and Geophysical Site Characterization, Barcelona, 18–21 June 2024* (pp. 226–233). Barcelona: Scipedia.

Mayne, P. W. & Liao, T. (2004). CPT-DMT interrelationships in Piedmont residuum. In *Geotechnical and Geophysical Site Characterization* (Vol. 2, pp. 345–350). Rotterdam: Millpress.

Mayne, P. W., Martin, G. K. & Schneider, J. A. (1999). Flat dilatometer modulus applied to drilled shaft foundations in Piedmont residuum. In *Proceedings of the ASCE Annual Convention, Charlotte (GSP 92): Behavioral Characteristics of Residual Soils* (pp. 101–112). Reston, VA: American Society of Civil Engineers.

Młynarek, Z. (2007). Site investigation and mapping in urban areas. In *Proceedings of 14th European Conference on Soil Mechanics and Geotechnical Engineering, Madrid* (Vol. 1, pp. 175–202). Rotterdam: Millpress.

Młynarek, Z., Gogolik, S. & Marchetti, D. (2006). Suitability of the SDMT method to assess geotechnical parameters of post-flotation sediments. In *Proceedings of the 2nd International Conference on Flat Dilatometer Testing* (pp. 148–153). Lancaster: In-Situ Soil Testing.

Młynarek, Z. & Sanglerat, G. (1983). Relationships between shear parameters and cone resistance for some cohesive soils. In *Proceedings of International Symposium In-Situ Testing, Paris* (Vol. 2, pp. 437–452). Paris: AIGI/IAEG.

Młynarek, Z., Stefaniak, G. & Wierzbicki, J. (2012). Geotechnical parameters of alluvial soils from in-situ tests. *Archives of Hydro-Engineering and Environmental Mechanics*, *59* (1–2), 63–81.

Młynarek, Z., Wierzbicki, J. & Long, M. (2008). Factors affecting CPTU and DMT characteristics in organic soils. In *Proceedings of 11th Baltic Sea Geotechnical Conference* (Vol. 1, pp. 407–417). Gdańsk: Gdansk University of Technology.

Morawski, W. (1984). *Osady wodno-morenowe*. Warszawa: Wydawnictwa Geologiczne.

Nepelski, K. A. (2020). *Numeryczne modelowanie pracy konstrukcji posadowionej na lessowym podłożu gruntowym*. Lublin: Wydawnictwo Politechniki Lubelskiej.

Orr, T. L. L. (2000). Selection of characteristic values and partial factors in geotechnical designs to Eurocode 7. *Computers and Geotechnics*, *26*, 263–279.

Pisarczyk, S. (2014). *Geoinżynieria. Metody modyfikacji podłoża gruntowego* (2 ed.). Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej.

Rabarijoely, S. (2000). *Wykorzystanie badań dylatometrycznych do wyznaczania parametrów gruntów organicznych obciążeniem nasypem* (PhD thesis). Szkoła Główna Gospodarstwa Wiejskiego w Warszawie, Warszawa [unpublished].

Rabarijoely, S. (2018). Dwa przykłady oceny osiadań budowli z wykorzystaniem badań dylatometrycznych (DMT). *Acta Scientiarum Polonorum. Architectura*, *17* (3), 103–119. https://doi.org/10.22630/ASPA.2018.17.3.33

Rabarijoely, S. (2019a). A new method for the estimation of hydraulic permeability, coefficient of consolidation, and soil fraction based on the dilatometer tests (DMT). *Studia Geotechnica et Mechanica*, *41* (4), 212–222.

Rabarijoely, S. (2019b). A Bayesian approach in the evaluation of unit weight of mineral and organic soils based on dilatometer tests (DMT). *Applied Sciences*, *9* (18), 3779. https://doi.org/10.3390/app9183779

Rasti, A., Adarmanabadi, H. R., Pineda, M. & Reinikainen, J. (2021). Evaluating the effect of soil particle characterization on internal friction angle. *American Journal of Engineering and Applied Sciences*, *14* (1), 129–138. https://doi.org/10.3844/ajeassp.2021.129.138

Robertson, P. K. (2009). CPT-DMT Correlations. *Journal of Geotechnical and Geoenvironmental Engineering*, *135* (11), 1762–1771.

Robertson, P. K. (2015). Comparing CPT and Vs liquefaction triggering methods. *Journal of Geotechnical and Geoenvironmental Engineering*, *141* (9), 04015037.

Robertson, P. K. & Cabal, K. (2022). *Guide to in situ testing*. *A concise and practical applications guide* (2 ed.). Retrieved from: https://www.greggdrilling.com/wp-content/uploads/2022/11/In-Situ-Testing-Guide-2022.pdf [accessed: 02.09.2025].

Schmertmann, J. H. (1978). *Guidelines for cone penetration test: performance and design* (No. FHWA-TS-78-209). Washington, D.C.: United States Federal Highway Administration.

Schmertmann, J. H. (1982). A method for determining the friction angle in sands from the Marchetti dilatometer test (DMT). In *Proceedings of the 2nd European Symposium on Penetration Testing (ESOPT 2), Amsterdam* (pp. 853–861). Rotterdam: A.A. Balkema.

Schmertmann, J. H. (1984). Comparing DMT with CPT in NC/OC sand bucket tests. *DMT Digest*, *4*.

Schneider, J. A., Hoyos, L. Jr., Mayne, P. W., Macari, E. J. & Rix, G. J. (1999), Field and laboratory measurements of dynamic shear modulus of Piedmont residual soils. In *Proceedings of the ASCE Annual Convention, Charlotte (GSP 92): Behavioral Characteristics of Residual Soils* (pp. 12–25). Reston, VA: American Society of Civil Engineers.

Szajna, W. S. (2015). Evaluation of the state of sandy soils on a sinkhole area with the use of noninvasive (MASW) and invasive (SDMT) tests. *Engineering Transactions*, *63* (1), 109–131.

Szajna, W. S. & Gontaszewska, A. (2015). Problems with the interpretation of results of DPL, CPTU and DMT tests in non-textbook sandy soil of lacustrine origin. *Osnovania i Fundamenty*, *37*, 27–37.

Tankiewicz, M. & Bagińska, I. (2021). Assessment and verification of correlations in CPTu testing on the example of soil from the Wroclaw surroundings (Poland). *Archives of Mining Sciences*, *66* (2), 313–327.

Tarnawski, M. (Ed.) (2020). *Badanie podłoża budowli. Metody polowe*. Warszawa: Wydawnictwo Naukowe PWN.

Truty, A. & Podleś, K. (2018). Numerical model of flat dilatometer test in cohesionless soils. In *4th International Symposium on Computational Geomechanics: ComGeo IV, 2–4 May 2018, Assisi, Italy: book of extended abstracts* (pp. 144–145). Rhodes, Greece, Swansea: International Centre for Computational Engineering (IC2E).

Wierzbicki, J. (2010). Ocena prekonsolidacji podłoża metodami in situ w aspekcie jego genezy. *Rozprawy Naukowe. Uniwersytet Przyrodniczy w Poznaniu*, *410*.

Wysokiński, L. (2007). Błędy systematyczne w rozpoznaniu geotechnicznym i ich wpływ na projektowanie budowlane. In *XXIII Konferencja Naukowo-Techniczna: Awarie budowlane, Szczecin–Międzyzdroje* (pp. 527–539). Szczecin: Wydawnictwo Politechniki Szczecińskiej.

Zabielska-Adamska, K. (2019). Water content–density criteria for determining geomembrane–fly ash interface shear strength. In *MATEC Web of Conferences* (Vol. 262, p. 04005). EDP Sciences. https://doi.org/10.1051/matecconf/201926204005

Zabielska-Adamska, K. (2020). Characteristics of compacted fly ash as a transitional soil. *Materials*, *13* (6), 1387. https://doi.org/10.3390/ma13061387

WYZNACZANIE ŚREDNICY ZASTĘPCZEJ CZĄSTEK PIASKU (D_{50}) NA PODSTAWIE BADAŃ DYLATOMETRYCZNYCH

STRESZCZENIE

Rosnące wymagania stawiane geotechnice wymuszają rozwój metod interpretacji umożliwiających uzyskanie jak największej liczby parametrów geotechnicznych z jednego profilu badawczego. Obszerne bazy danych z udokumentowanych punktów badawczych wykorzystano do skonstruowania i opracowania bezpośredniej współzależności między zmierzonymi dylatometrem Marchettiego (DMT) ciśnieniami (p_0, p_1) a wynikami badań laboratoryjnych uziarnienia gruntów niespoistych z próbek uzyskanych z otworów wiertniczych. Ponadto w analizie uwzględniono ciśnienie wody w porach (u_0). Głównym osiągnięciem artykułu jest uzyskanie oryginalnej współzależności, która umożliwia oszacowanie wartości

średnicy zastępczej (D_{50}) gruntów niespoistych bezpośrednio na podstawie wyników badań DMT. Ponadto obliczone na podstawie proponowanej współzależności wartości D_{50} zostały zweryfikowane przy użyciu wyników badań laboratoryjnych gruntów z innych obiektów nieuwzględnionych w analizie podczas opracowywania proponowanej współzależności empirycznej.

Słowa kluczowe: badanie in situ, grunt mineralny, uziarnienie piasku

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REVIEW PAPER

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COMPARATIVE ANALYSIS OF THE OPTIMAL LOCATION FOR A NEW PUBLIC NURSERY: A CASE STUDY OF THE CELESTYNÓW COMMUNE

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ABSTRACT

This article presents a comparative analysis of potential locations for a new public nursery in the Celestynów Commune. The study employs a multi-criteria evaluation approach, integrating spatial, environmental, and social factors to identify the optimal site. Key aspects considered include accessibility, safety, proximity to residential areas, and environmental conditions such as sunlight exposure and noise levels. Analysis based on field observations and collected baseline data highlighted the benefits and trade-offs associated with each proposed location. The findings provide valuable insights for local planners and decision-makers to ensure the nursery's location promotes accessibility, child safety, and a healthy developmental environment. This case study illustrates how systematic pre-design assessments can effectively guide public infrastructure placement in small communities.

Keywords: public nursery, site selection, spatial analysis, urban planning, community development, Celestynów

INTRODUCTION

The establishment of early childhood education facilities is a critical component of community development, shaping not only the educational landscape but also influencing social and spatial dynamics within localities. In contemporary urban and suburban settings, the demand for accessible, affordable and well-equipped nursery spaces reflects broader demographic trends and societal shifts towards supporting young families (Palley & Usui, 2008). Various reports show that accessibility to nurseries differs between urban, suburban and rural areas, and remains difficult in the latter. As people in Poland choose educational institutions largely based on their location, it becomes a crucial factor (Baczko-Dombi, Komendant-Brodowska & Zając, 2015). Currently, only a small portion of the population in Poland uses institutional childcare for children under three years old. Changing that could also support the professional activity of mothers who do not want to remain outside the labour market for too long, thereby benefiting the economy (Piętka-Kosińska & Ruzik-Sierdzińska, 2010). In some cases, an apparent surplus of nursery places over the number of children is misleading; it does not result from a systematic excess of supply over demand for these places, but from problems resulting from the data collection system (Kurowska & Szczupak, 2016). Data from Statistics Poland (GUS) show that in Poland, the universality of care provided by nurseries and children's clubs is increasing, but it is still far from

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meeting the revised Barcelona goals (Racław, 2024). As Blumsztajn (2007) points out, the high educational quality of the facilities, their accessibility and their flexibility and adaptation to the needs of working parents seem to be the aspects that should be most emphasised when considering a childcare system for young children.

When planning such facilities, the decision regarding their location and the form of their integration into the existing urban fabric is paramount. The spatial distribution of preschool education facilities is one of the crucial factors in their accessibility (Wang, Zhao, Lu & Li, 2024). These choices affect not only the usability and functionality of the facility but also its accessibility, safety, and long-term sustainability (Ratajczak & Basińska, 2021; Ambrose et al., 2024). Spatial analyses of similar character – regarding the optimal location for a specific building – were conducted and published; however, they are not limited to nurseries. Some of those studies used GIS-based systems to evaluate current locations and suggest alternative spatial arrangements (Köse, Koçyiğit, Erdem & Jega, 2021). In other cases, it is not only the location that is being analysed, but broader, multi-criteria models are used for decision-making regarding the adaptations of buildings (Nedeljkovic, Jurenic & Djokic, 2023; Starzyk et al. 2023). Interestingly, the location of the analysed buildings appears vividly throughout those models. Parallelly, there are multiple studies on educational buildings that concentrate on the quality of architecture, particular design solutions, and how they affect and meet the needs of its different users (Moura e Sa & Saraiva, 2001; Astaresh, Fakhimzade & Rezaee, 2015; Lindén et al., 2024; Sungur, 2024).

In the case of the Celestynów Commune, two principal strategies emerge for meeting the demand for new facilities through the adaptation of existing kindergarten infrastructure. The first involves expanding the current kindergarten building to encompass nursery functions, thereby creating a multi-age educational environment that maximises resource use and site potential. The second approach proposes a complete conversion of an existing kindergarten facility into a dedicated nursery space, focusing on tailoring the environment specifically for the developmental needs of infants and toddlers.

Both scenarios necessitate comprehensive architectural modifications to ensure appropriate internal layouts, safe and stimulating environments, and compliance with regulatory standards for younger children. The surrounding outdoor spaces must be adjusted to provide age-appropriate play areas. It is especially important to provide access to nature in the places where children live, play, and learn (Chawla, 2015). While the degree of urbanisation had significant negative influences on the frequency of direct experiences of nature (Soga, Yamanoi, Tsuchiya, Koyanagi & Kanai, 2018), the suburban commune of Celestynów offers relatively good access to it. However, given the limited mobility of children of nursery age, accessibility to nature is significantly different from that of adults and should be carefully considered. Additionally, technical infrastructure upgrades are required to support the enhanced needs. Universal design adaptations benefit the overall inclusiveness and spatial accessibility (Jung, Elsamanoudy & Abdelaziz Mahmoud, 2025). Such transformations illustrate the complexities inherent in repurposing educational buildings, where balancing functional requirements, budget constraints, and community expectations becomes a delicate task.

Through a comparative analysis of these alternatives, this study aims to provide evidence-based recommendations to guide local authorities and planners in making decisions about nursery development. By assessing spatial, functional, and infrastructural factors, the study contributes to the ongoing discourse on efficient and effective early childhood education facility planning, with implications extending beyond Celestynów to similar communities facing comparable challenges.

MATERIAL AND METHODS

This study presents an original analysis aimed at identifying the optimal location for a new public nursery within the existing urban fabric of the Celestynów Commune. It is based on work commissioned in 2023 and was prepared along with a design concept in the architectural studio AMIRI architekci (Amiri, 2023).

The evaluation focused on two potential sites involving either the expansion of an existing kindergarten facility to include nursery functions or the complete conversion of a kindergarten building into a nursery. Both options required consideration of architectural modifications, landscape adjustments, and technical infrastructure upgrades to meet the specific needs of younger children.

Data for the analysis were gathered from municipal records and site inspections. The selection criteria included accessibility, proximity to residential areas, suitability of the existing building layout for adaptation, and compliance with current safety and educational standards. The study integrates spatial analysis with consultations involving local stakeholders to ensure alignment with community needs and expectations.

The findings are supported by graphical presentations and tabular data, drawing on pre-design assessments, architectural standards, and the relevant literature. Conclusions are derived from this comprehensive evaluation.

RESULTS

Site analysis and comparison

This section presents a detailed comparative analysis of two potential locations for the new public nursery, focusing on terrain conditions, existing infrastructure, and potential for expansion.

Location A is situated in the densely developed village centre of Celestynów, approximately 350 m from its centre, the municipal cultural and sports centre, and the public library, and about 1 km from the train station. The site covers an area of 5,559.5 m^2 and currently hosts a two-storey kindergarten building with a footprint of 1,346 m^2 (Table 1). Adjacent to the building is a large car park with approximately 40 spaces and a playground for kindergarten children. The building, shaped in a T-plan with a sloped roof, accommodates eight kindergarten classes and related facilities. Its southwestern position on the plot, coupled with existing tall trees primarily along the northern boundary, suggests that the most viable expansion option involves extending the southern part of the building to preserve adequate sunlight for new classrooms (Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r.). The site is well-equipped with utilities, including stormwater drainage, sanitary sewerage, electricity, telecommunications, gas, and water connections. Additionally, the presence of low vegetation within the area is unlikely to impede expansion plans. There is no direct connection to nature apart from a few trees along its northern border.

Location B is in Stara Wieś, a village in the northern part of the Celestynów Commune, approximately 80 m from a primary school and 250 m from a train station. The plot, with an area of 2,317.4 m^2, includes a kindergarten facility comprised of a historic residential building converted for educational use, alongside an adjacent newer structure added in 2011 (Table 1). Both original and expanded sections feature a sloped roof. The building is elevated approximately 50 cm above the surrounding ground level. A green playground area is situated in the northern part of the plot. The orientation of the building favours placing new nursery units on the northern side to capitalise on east and west sun exposure (Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 25 maja 2023 r.). Existing infrastructure includes water and sanitary sewerage within the site, with nearby access to electricity and gas from adjacent roads. The presence of a single tall tree and some low shrubs around the plot's perimeter may require consideration during expansion (Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 25 maja 2023 r.). Despite the short distance to the forest, the site is separated by a street that effectively prevents access to it for children of nursery age.

Comparatively, Location A benefits from its central position within the commune, with immediate access to several public amenities, making it more accessible and potentially more attractive to parents. Furthermore, the village of Celestynów, with approximately 5,000 inhabitants, is the biggest in the commune, which further supports this location. Conversely, Location B, situated on the commune's outskirts, offers more available open space on the plot (Table 1), allowing for expansion with fewer constraints to the existing building structure and playground. This spatial advantage facilitates the creation of new, age-appropriate playground facilities.

Table 1. Existing land development in both locations

Specification	Area [m^2]		Share in the general area [%]	
	Location A	Location B	Location A	Location B
Plot area	5,559.53	2,317.40	100	100
Existing buildings	1,346.18	334.80	24.21	14.44
Roads and car parks	916.47	0	16.48	0
Pavements	499.29	64.8	8.98	2.80
Building perimeter	56.03	41.54	1.01	1.79
Greenery	2,598.01	1,876.26	46.74	80.97
Safe surfaces	143.55	0	2.58	0

Source: AMIRI architekci (Amiri, 2023).

Although both sites are outside the boundaries of the current local development plans, they are designated in the commune's spatial study as suitable for kindergartens and public schools. Both locations are connected to necessary utilities, supporting their potential for adaptation to the nursery function (Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 6 marca 2025 r.).

In conclusion to this section, Location A is favoured for its centrality and integration with community resources, while Location B offers greater spatial flexibility for expansion. Further planning must balance these factors to determine the optimal site for the new public nursery.

Existing architecture

This section examines the architectural characteristics, construction quality, and accessibility features of the two potential nursery locations.

Architectural form

Location A features a two-storey building constructed using traditional techniques, capped with a sloped roof. The ground floor houses kindergarten classrooms primarily in the western wings, along with changing rooms and a kitchen. The attic contains offices, administrative spaces, and a boiler room; however, a significant portion of the attic remains unfinished and undeveloped.

Location B comprises a former two-storey residential building adapted for kindergarten use, with a northern extension added in 2011. The ground floor of the original structure accommodates play areas, changing rooms, and a boiler room, while the attic includes children's rooms and a common area. The building features two sloped roofs corresponding to the original and expanded sections. Notably, the attic layout does not comply with current fire safety regulations or standards concerning height and natural lighting according to currently applicable regulations concerning the technical conditions of buildings and their location (Table 2).

Table 2. Existing architecture in both locations

Specification	Location A	Location B
Number of storeys	2 above ground level	2 above ground level
Building height [m]	8.60	8.10
Building length [m]	34.26	19.79
Building width [m]	61.21	20.75
Usable area [m^2]	2,011.74	279.72
Building area [m^2]	1,346.18	334.80

Source: AMIRI architekci (Amiri, 2023).

Construction quality

Both buildings were erected using traditional construction methods. Location A is reported to be in good technical condition, with reinforced concrete ceilings. In contrast, Location B's original structure, designed for residential purposes, will require evaluation to verify the adequacy of the ceiling strength for continued nursery use on the upper floor according to currently applicable regulations concerning the technical conditions of buildings and their location. The 2011 extension is single-storey and similarly constructed using traditional techniques.

Accessibility

Both locations offer external ramps facilitating access for wheelchair users and caregivers with children. However, neither building is equipped with a lift, rendering the second floor inaccessible to individuals with mobility impairments. Location A includes a toilet adapted for people with disabilities, whereas Location B lacks such facilities, but they are necessary according to currently applicable regulations concerning the technical conditions of buildings and their location (Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 6 marca 2025 r.).

Recapitulation

Location A presents a structurally sound two-storey building, erected with traditional construction methods. The absence of a lift, however, restricts access to the upper floor for users with disabilities. Location B, originally a residential structure adapted for kindergarten use, requires careful structural assessment, especially concerning ceiling strength and fire safety compliance. Accessibility limitations are similar to those of Location, compounded by the absence of accessible toilets. Future modernisation and expansion plans for both locations must address compliance with fire safety, room height, and natural lighting regulations to ensure a safe, functional environment for children and staff (Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r.). Additionally, integrating accessibility features such as lifts and accessible toilets is essential to provide equitable access for all users, regardless of physical ability.

Site design concept

In the course of design development, two variants were proposed – each tailored to one of the analysed sites (Figs 1 and 2). These proposals focus on the adaptation of existing kindergarten plots to accommodate nursery functions, while addressing safety, accessibility, and outdoor space requirements.

At Location A, the primary access to the site remains unchanged, with entry provided from the east via Szkolna along an internal road. Similarly, Location B retains access from the northeast, via Mickiewicza. In both locations, the existing vehicular approaches are deemed sufficient, particularly in terms of compliance with fire vehicle access regulations. At Location A, the internal road system meets the 30-metre access requirement, while at Location B, emergency vehicles are able to approach directly from the adjacent public street (Rozporządzenie Ministra Spraw Wewnętrznych i Administracji z dnia 24 lipca 2009 r.).

Parking conditions differ between the two sites. Location A already offers approximately 40 on-site parking spaces, and no further expansion is planned, as this capacity is currently considered adequate. Location B, on the other hand, lacks dedicated on-plot parking. As part of the development proposal, reliance on existing parallel parking along Mickiewicza is anticipated. While both sites presently meet functional requirements, final decisions regarding parking adequacy will depend on local planning and building permit stipulations.

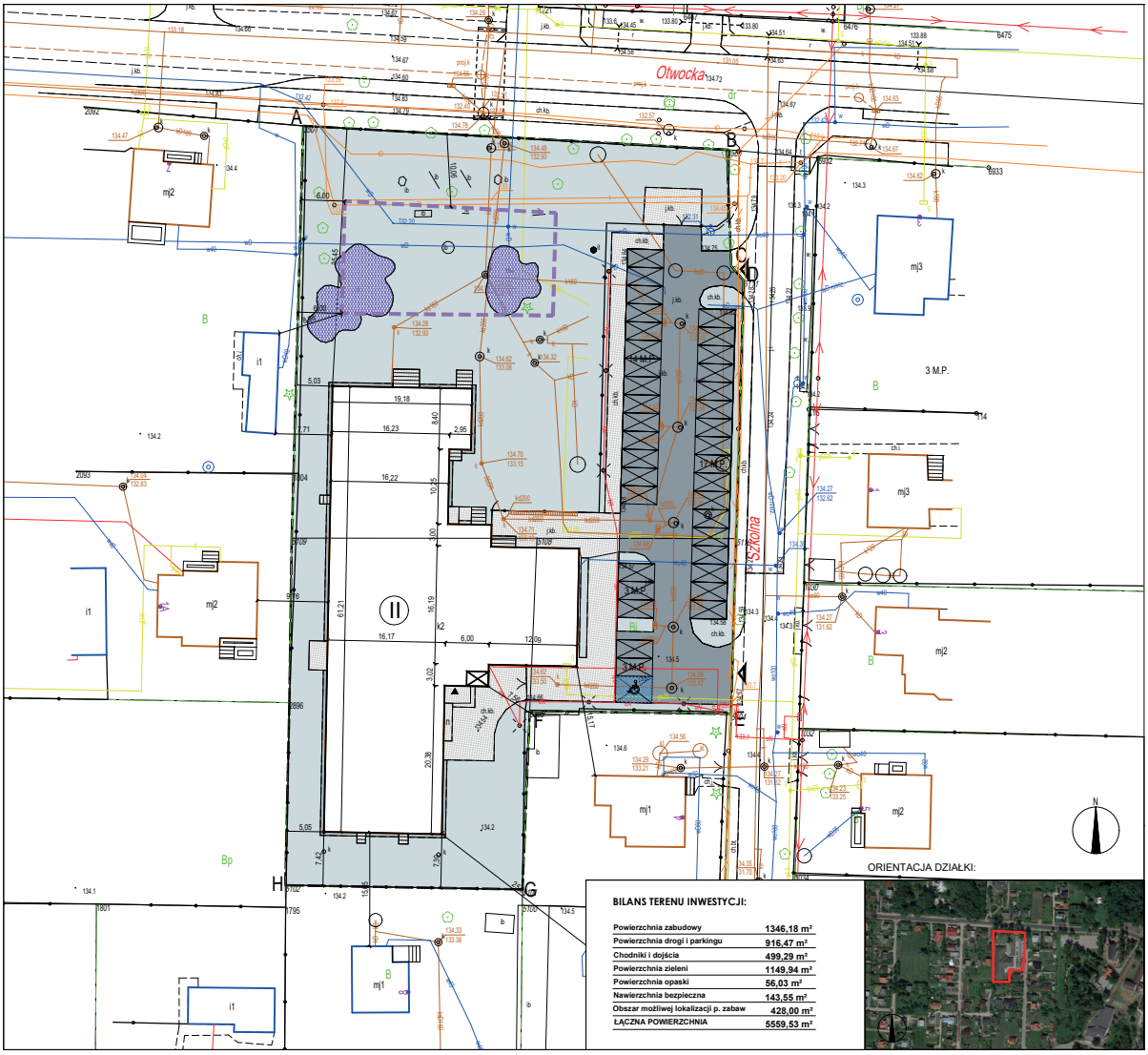


Fig. 1. Site design in Location A (Celestynów)

Source: AMIRI architekci (Amiri, 2023).

Pedestrian access and circulation are more significantly impacted at Location B. In Location A, the existing pedestrian paths are expected to remain in use without modification. However, the reorganisation of the main entrance at Location B requires the introduction of a new walkway and ramp system. These changes are intended to bridge a slight elevation difference between the existing and expanded sections of the building and to ensure full accessibility for individuals with limited mobility in accordance with universal design standards.

Outdoor space plays a critical role in early childhood facilities, and both proposals integrate playground design into the site planning process. Each plot complies with national spatial regulations regarding minimum distances between playgrounds and nearby boundaries, waste collection areas, and building openings (Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r.). In Location A, the playground

will be upgraded and reconfigured to meet the requirements of nursery-aged children. In Location B, where the existing kindergarten will be entirely converted to a nursery, the entire playground area will require reprogramming and new equipment installation. In both cases, sufficient space is available to accommodate the necessary adjustments, with the proposed playground area in Location B totalling 198.4 m^2.

Terrace spaces have also been incorporated to support the developmental needs of infants and toddlers. According to §4(2) of the Regulation of 7 December 2018, concerning sanitary standards for nurseries and children's clubs, access to outdoor space such as verandas or terraces should be provided (Obwieszczenie Ministra Rodziny, Pracy i Polityki Społecznej z dnia 7 grudnia 2018 r.). Location A includes terraces on both levels of the building, located on the southern façade and accessible from nursery rooms on the first floor. In contrast, Location B offers a single ground-level terrace on the northern side, designed for direct access to both indoor nursery spaces and the adjacent playground. In terms of facilities for waste storage, both sites are already equipped with dedicated shelters, and no additional infrastructure in this regard is necessary.

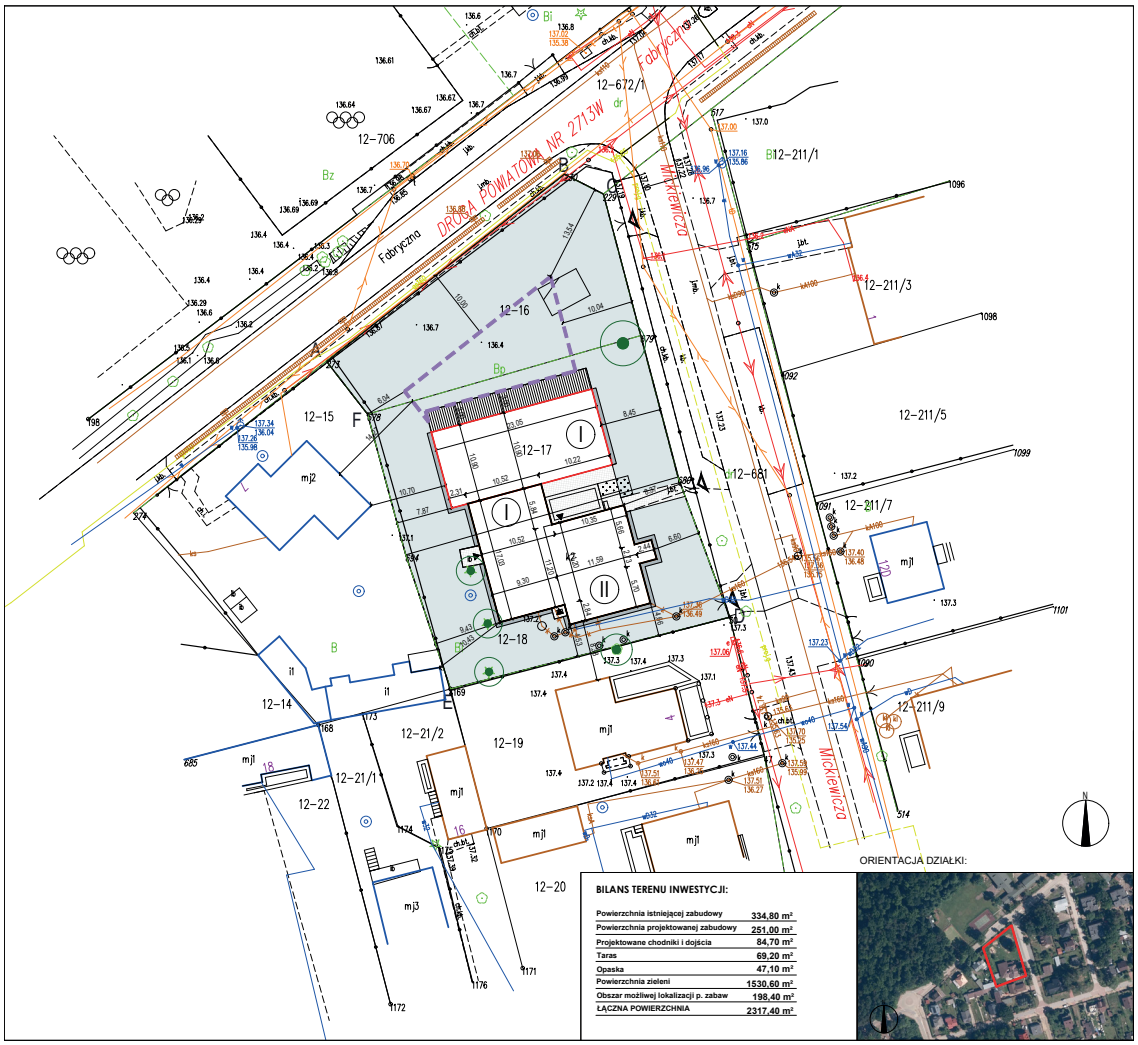


Fig. 2. Site design in Location B (Stara Wieś)

Source: AMIRI architekci (Amiri, 2023).

Overall, neither of the proposed design concepts requires substantial alterations to the existing landscape. Both sites offer adequate fire and vehicular access, potential for accessible pedestrian circulation, and space for age-appropriate outdoor activities. Location A benefits from a more developed internal infrastructure, particularly in terms of parking and existing walkways, while Location B requires minor modifications to achieve the same level of functionality (Table 3). Both sites demonstrate strong potential for successful adaptation to nursery use.

Table 3. Designed land development in both locations

Specification	Value [m^2]		Share in the general area [%]	
	Location A	Location B	Location A	Location B
Plot area	5,559.53	2,317.40	100	100
Existing buildings	1,346.18	334.80	24.21	14.44
Building expansion	0	251.00	0	10.83
Roads and car parks	916.47	0	16.48	0
Pavements	499.29	84.70	8.98	3.65
Terrace	0	69.20	0	2.99
Building perimeter	56.03	47.10	1.01	2.03
Greenery	2,598.01	1,530.60	46.74	66.06
Safe surfaces	143.55	0	2.58	0
Area of the potential playground location	428.00	198.4	7.70	8.56

Source: AMIRI architekci (Amiri, 2023).

Architectural concept

The architectural proposals for both Location A and Location B involve tailored interventions designed to expand nursery facilities while responding to the constraints and qualities of the existing buildings. In both cases, the goal is to improve functionality, ensure compliance with accessibility standards, and minimise disruption to the architectural integrity of the original structures.

At Location A, the proposal centres on extending the building's southern and central zones to accommodate new nursery rooms, a meal distribution centre, and dedicated administrative space. The northern portion, where no expansion is planned, is intended for office and administrative use – both for the nursery and to compensate for the kindergarten's facilities displaced by the installation of a new lift (Fig. 3).

The roof form in the southern section must be adjusted to allow for the creation of a terrace with direct access from the nursery rooms, a functional requirement that necessitates significant architectural modifications. A lift is to be introduced at the edge of the building, replacing the former porter's lodge. This placement has been selected to minimise structural disruption, though changes to the roof and the addition of a vertical shaft are still required. In addition, a freight lift will be installed to transport meals from the kitchen to the second-floor distribution centre, resulting in further modifications to both structure and function. The ground-floor porter's office and the first-floor nurse's room will be removed as part of these changes. Their functions will be relocated: administrative offices and a new nurse's office are planned for the northern section, while three new nursery units will be in the south. The new roof and façade elements generated by these extensions are to be harmonised with the architectural character of the existing building to preserve its visual coherence and heritage value (Fig. 4).

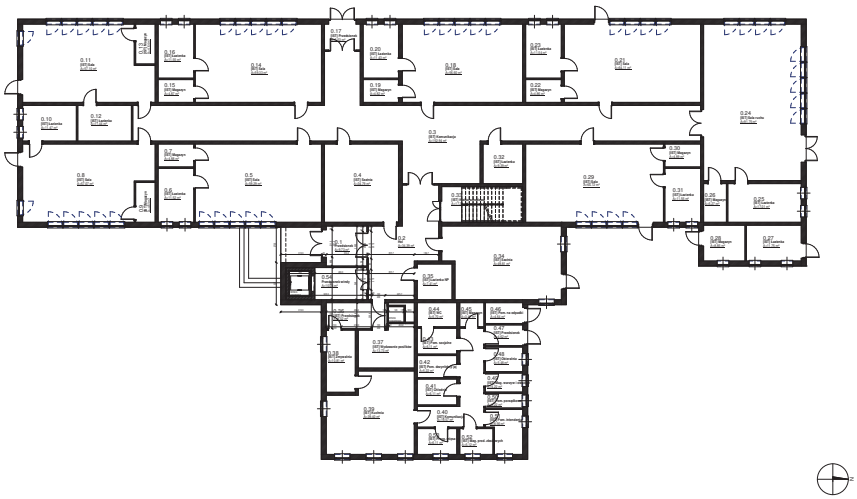


Fig. 3. Ground floor plan in Location A (Celestynów)

Source: AMIRI architekci (Amiri, 2023).

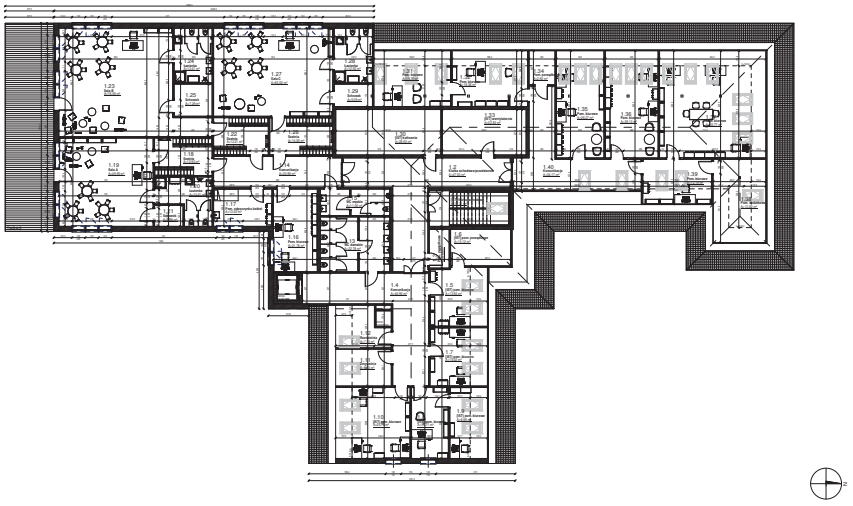


Fig. 4. First floor plan in Location A (Celestynów)

Source: AMIRI architekci (Amiri, 2023).

In contrast, the architectural strategy for Location B involves constructing a new, single-storey structure on the northern side of the existing building (Fig. 5). This addition, conceived as a separate but visually integrated component, will be structurally independent. Designed to be consistent with the original architectural language, it will require adjustments to the existing annexe's roofline and stormwater drainage. The new section will house two nursery units, complete with locker rooms, toilets, and supporting technical and administrative spaces.

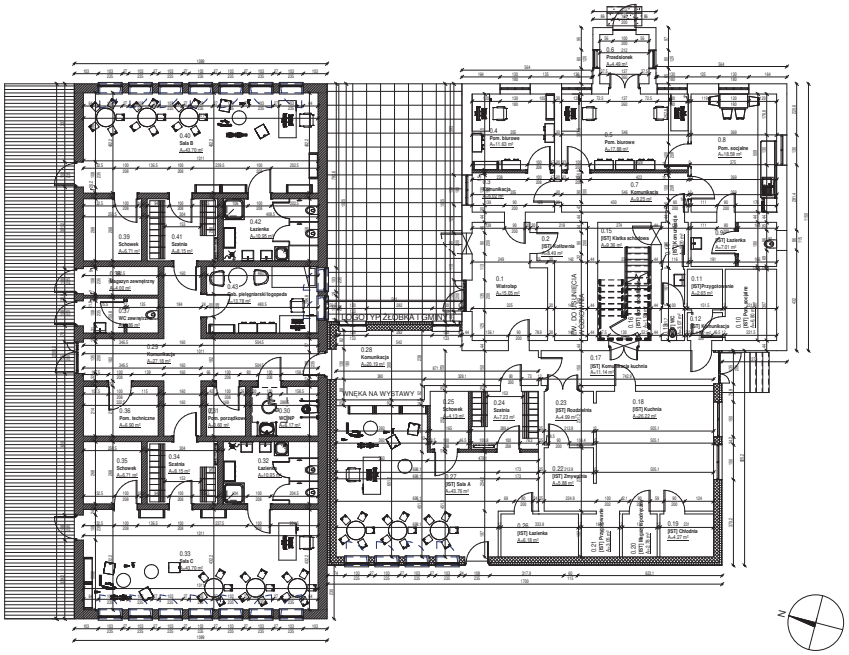


Fig. 5. Ground floor in Location B (Stara Wieś)

Source: AMIRI architekci (Amiri, 2023).

Inside the existing building, selective alterations to partition walls are planned to accommodate new locker rooms and reallocate administrative offices. The first floor, however, is to be closed entirely, as the rooms located there do not meet current fire safety or spatial standards (Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r.). The building's oldest section will be repurposed using existing partition walls, ensuring a minimal level of intrusion.

Construction considerations

Location A involves extensive structural work. To admit sufficient natural light into the upper rooms, significant modification of the roof's wooden truss is required – effectively amounting to an additional floor. A structural analysis of the ground floor ceiling is essential to assess whether it can bear the new loads; reinforcement may be needed, especially around the lift shaft. The installation of the passenger lift, while aligned with an outer wall for ease of construction, entails foundational intervention and the introduction of a pit, adding to the project's complexity. Given the invasive nature of the work, temporary or complete closure of the building during the construction phase will likely be unavoidable (Table 4).

Location B, by contrast, poses fewer structural challenges. The new building will not impose loads on the existing one due to the expansion joint. However, the northern portion of the existing roof must be redesigned to ensure proper water runoff, as the current slope directs water toward the proposed extension. Should the 2011 annexe be affected, the existing northern windows would need to be removed, and new ones added on the western façade. A new compliant entrance door will be inserted into the northern elevation. There is also potential to relocate the boiler room to the new part, but this would necessitate designing an independent heating system for each part of the complex. Functional changes to the original building, such as widening previously sealed openings, are minimal and structurally non-invasive (Table 4).

Table 4. Designed architecture in both locations

Specification	Location A	Location B
Number of storeys	2 above ground level	1 above ground level (existing attic closed for use)
Building height [m]	8.60	8.10
Building length [m]	34.26	27.89
Building width [m]	61.21	20.75
Usable area [m^2]	2,009.92 (of which 654.3 redesigned)	151.59
Building area [m^2]	1,346.18	319.97

Source: AMIRI architekci (Amiri, 2023).

Accessibility

Accessibility requirements inform both proposals, albeit with differing levels of complexity. At Location A, a passenger lift must be added to enable full access to the first floor. While this intervention is relatively contained, it still requires modifications to the roof and vertical circulation core. Although an accessible toilet exists on the ground floor, a similar facility must be provided on the upper level. Corridors, both existing and proposed, are sufficiently wide to support barrier-free movement.

Location B is designed with accessibility from the outset. All door widths and access points in the new section accommodate individuals with reduced mobility, and an accessible toilet is included. Since the upper floor of the old building will be closed, the need for a lift is effectively eliminated, streamlining compliance with accessibility standards (Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r.).

Recapitulation

Location A, while offering logical functional arrangements, presents several architectural and technical challenges. The necessity of raising part of the building and altering the rooflines has significant implications for the building's external appearance and structural performance. While the design addresses immediate needs, its long-term architectural impact remains uncertain.

Location B appears more promising in terms of both construction feasibility and architectural cohesion. The proposed extension, designed as a second wing, offers an opportunity to restore a sense of symmetry and completeness to the complex. Moreover, this expansion could visually reconcile the somewhat disjointed 2011 annexe with the older structure. Internally, after removing some secondary partitions, it would be possible to create a large, flexible space with sanitary facilities – potentially serving a range of future functions beyond nursery use.

In both scenarios, compliance with accessibility and building regulations is a critical factor. However, the overall construction burden is significantly higher in Location A, and the visual outcome of its extension remains difficult to anticipate. Location B, while not without its constraints, offers a clearer architectural resolution and a more manageable construction process.

Fire safety

Category

Both proposed sites fall under the ZL II classification, indicating buildings intended primarily for use by individuals with limited mobility (Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r.). This classification carries specific requirements related to evacuation, fire resistance, and accessibility, all of which have been incorporated into the respective architectural concepts for each location.

Building and fire-resistant class

In the case of Location A, the building is a low-rise (N-class building), two-storey structure exceeding 750 m^2 in usable area. As such, it requires a fire resistance Class C, which necessitates the use of fire-retardant materials and the introduction of a fire separation wall (Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r.). These design features ensure the containment of fire and smoke, especially in larger and vertically developed buildings.

Conversely, Location B comprises a low-rise (N-class building), single-storey structure. According to fire safety regulations applicable to ZL II buildings of this scale, a fire resistance of Class D is deemed sufficient. This distinction not only reflects the lower fire resistance needed but also reduces the complexity of required construction measures.

Spatial placement and distances for fire safety

The spatial positioning of buildings in relation to adjacent structures plays a crucial role in passive fire protection strategies. Location B maintains a compliant minimum distance of 8 m from neighbouring ZL and PM category buildings, in accordance with applicable regulations. However, Location A does not meet this requirement due to the proximity of surrounding structures to the plot boundary. As such, the implementation of the project in Location A will necessitate obtaining a derogation from fire separation distance regulations. This will entail additional administrative procedures and may lengthen the project timeline. Furthermore, the proposed placement assumes that the roofs of neighbouring buildings meet a minimum fire resistance rating of RE30 – an assumption that must be verified during the construction documentation phase.

Evacuation

The evacuation strategies for both locations have been carefully designed to meet the strict criteria set forth for ZL II buildings. In Location A, corridor lengths on the first floor do not exceed the 10-metre evacuation distance to the next fire zone in places with only one evacuation route, and all nursery room doors are designed to open outward to facilitate rapid evacuation in rooms accommodating more than six people. The length of evacuation routes remains within the 40-metre limit (with two or more evacuation routes) and avoids passage through more than three rooms. Corridor widths are designed to meet the 140 cm minimum requirement, ensuring sufficient space for the movement of individuals, including those with limited mobility.

In Location B, similar fire safety provisions have been implemented. Corridors and evacuation paths do not exceed regulatory length limits and provide direct access to the outside. Door orientation and corridor widths follow the same rules as in Location A. An additional benefit of this site is that many rooms allow direct evacuation to the exterior, which enhances safety. However, the first floor of the older part of the building must be closed for use, as the existing staircases do not conform to fire safety regulations concerning both the width of evacuation stairways and the maximum allowed length of evacuation routes (Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r.). Achieving compliance in this regard would require extensive structural modifications, which have been deemed impractical within the current project scope.

Sanitary regulations and food provision

Sanitary facilities and ventilation

In Location A, following the anticipated expansion, more than twenty women are expected to be employed simultaneously in the building. In accordance with applicable regulations, the inclusion of an additional, dedicated women's toilet is required. On the first floor, new toilets are being designed adjacent to each nursery room, ensuring that every nursery unit is equipped with sanitary facilities that meet the regulatory

standards. Additionally, employee toilets for the office and administrative areas are being expanded to accommodate the increased number of staff. The placement of all new toilets has been strategically planned to utilise the existing shafts, thus minimising the need for extensive infrastructural modifications. It is further recommended that the facility be equipped with a mechanical ventilation system, enhancing indoor air quality and aligning with contemporary hygiene standards for childcare environments.

In Location B, the newly designed nursery units include toilets that comply fully with current regulatory standards. Across the facility, two toilets are accessible to staff: one located in the new section of the building, designed to accommodate individuals with disabilities, and a second, pre-existing toilet situated near the staircase. However, this existing facility will require adaptation to meet contemporary sanitary regulations. The proposed alterations ensure compliance while maintaining the building's operational continuity.

Food provision and kitchen facilities

In Location A, given the vertical functional division and the requirements imposed by sanitary regulations, it is necessary to create a food distribution centre and a dedicated washing room on the first floor. These spaces must be functionally connected to a freight lift, allowing efficient vertical transport of food from the kitchen to the nursery units. The existing kitchen has been assessed as adequate in terms of size and capacity, and no enlargement is required to support the new nursery units. The integration of these service functions within the existing structural layout facilitates regulatory compliance without major reconstruction.

In Location B, the number of children to be accommodated remains similar to current levels. However, the existing kitchen infrastructure fails to meet sanitary regulations. Key deficiencies include the intersection of "clean" and "dirty" pathways, the absence of essential functional spaces, and a limited usable area. To comply with current hygiene and food handling standards, the kitchen would need to be expanded by approximately 50–70% of its current size.

To meet that demand, two alternative approaches are proposed. The first involves direct expansion of the kitchen, which could be achieved by repurposing part of the adjacent unit. This would, however, lead to the reduction of nursery space, necessitating the creation of an additional nursery unit elsewhere. To mitigate this impact, a redistribution of administrative spaces could be considered – relocating one or two offices from the existing building to the new annexe. Consequently, the nursery units in the new extension could be enlarged (e.g. accommodating two groups of 23 children instead of three groups of 15), thereby maintaining the facility's overall childcare capacity.

The second approach would be to exclude the section containing the kitchen from the scope of the current development project. While this option avoids expansion costs, it would require formal approval from multiple authorities, including the architectural department, the sanitary inspectorate, and other relevant agencies overseeing final commissioning. Its feasibility depends on external administrative decisions and thus introduces uncertainty into the implementation timeline.

Additionally, in Location B, the facility's entrance area must be redesigned to ensure direct, hygienic circulation between the kitchen and the nursery units. Current spatial arrangements require food to be transported through the main vestibule – a practice that is not compliant with sanitary standards.

CONCLUSIONS

Analyses prepared for a particular building type in a particular municipality or commune often remain in the form of a technical report and are usually not intended for publication. One of the reasons might be that these documents are thought to be of marginal use for the broader public, given the selective goal, target audience and adopted perspective. The other might be that they contain information that is considered not intended for publication, especially that of a financial nature. It is therefore challenging to form a suitable

comparison of aspects that are taken into consideration while choosing a proper location for an educational building, notably for a nursery. The specificity of a case study hinders a broader application, yet there are facets that can be found in analogous studies and thus are worth emphasis. This study is focused on those that could be conveniently ubiquitous. The discussed aspects can be profitably analysed in similar processes in the future, in spite of the exact level of education – it can be appropriately adjusted to nurseries, kindergartens and possibly schools. Public institutions seeking to broaden their educational offer could benefit from applying them to particular cases of their own, which could lead to optimising the process and result in choosing the appropriate location for a new building or new public service.

The comparative analysis of the two locations – Location A in central Celestynów and Location B in Stara Wieś – highlights a fundamental trade-off between centrality and implementation feasibility. Location A benefits from proximity to other public services and the existing social infrastructure, offering convenience for local families. However, its constrained spatial conditions and structural limitations present significant challenges for expansion. In contrast, Location B, although located in a smaller and less central village, offers greater architectural flexibility and fewer logistical complications during construction (Gao, Wargocki & Wang, 2014).

The technical assessment reveals that Location A would require complex and costly interventions, such as roof reconstruction, ceiling capacity assessment, and the installation of vertical circulation elements, including a passenger and freight lift. These works would likely make the building temporarily unusable, directly affecting the 175 children currently using the facility. Additionally, the architectural risks associated with integrating a superstructure on top of an existing, recently built facility raise concerns regarding both aesthetics and structural integrity.

Location B, while facing issues such as the need to redesign and expand a non-compliant kitchen, offers a more straightforward implementation path. The building would be unoccupied during construction, and the necessary changes – such as layout reorganisation or constructing a new wing – are less invasive and technically more predictable. Furthermore, the site offers opportunities for longer-term development, including the potential to build a completely new nursery facility with an adjacent playground, should funding and permissions allow.

From an economic standpoint, the investment in Location B is more cost-effective. The expansion approach allows for lower material and labour costs compared to the superstructure planned at Location A. The preliminary estimation demonstrated a difference of approximately doubling the costs, yet exact figures are not to be published. Additionally, Location B permits continued usage of the existing Celestynów nursery facility without disruption, while also opening possibilities for mixed-use programming – such as spaces for seniors – which aligns with broader goals for community integration and sustainable development.

In evaluating the two sites, several criteria were considered, including cost, safety, functional layout, and long-term potential. While Location A has advantages in centrality, user convenience, and combining nursery and kindergarten functions, these are offset by complex structural requirements and higher construction risk. It remains valuable for future adaptive reuse – potentially serving various community purposes at a lower financial threshold – but it is less suited for immediate nursery expansion given its current use, structural complexity, and higher associated costs.

Location B demonstrates a clear advantage in most of the criteria: cost-efficiency, safety (due to ground-floor-only layouts), aesthetics and implementation logistics, with the added potential of developing a flexible function. Ultimately, the findings suggest that it offers a more viable and sustainable path for meeting the Celestynów Commune's goal of adding 45 new nursery places. It allows for a more phased, adaptable investment strategy with minimised disruption to ongoing educational services. It is definitely more cost-effective, it has the potential of becoming an intergenerational space for the local community, and given the technical issues regarding the possible expansion, it is more sustainable.

The concluding point of this study should, however, not be a specific detail of the performed analysis between these two locations, but rather a general view on the matter of accessibility and how it can, and perhaps should, be perceived. The choice of optimal location for a public nursery is nonetheless a question of its accessibility.

As Racław (2024, p. 28) emphasised: "In the field of care and early education services, accessibility takes on many aspects: territorial (regions/areas), location (distance from home/workplace), architectural and equipment (adaptation of buildings, equipment, furnishings), price (affordability of fees), compatibility/flexibility (adaptation to the mode and hours of work of parents, taking into account commuting), categorical (specific groups of service users and their needs) and in terms of staff competences (professionalisation and development) [author's transl.]."

It is with that viewpoint that a study intended as a technical report might encourage adopting a broader perspective.

REFERENCES

Ambrose-Oji, B., Pearson, M., Cross, E., Shallcross, J., Polschneider, S., Hattersley, R. & FitzGerald, O. (2024). Community Tree Nurseries in the UK: Promise, Potential and Pitfalls. *Forests*, *15*, 560. https://doi.org/10.3390/f15030560 [accessed: 22.07.2025].

Amiri, O. (2023). *Documentation of the comparative analysis of two potential locations for the investment involving the creation of new nursery places in Celestynów commune* [unpublished].

Astaresh, M., Fakhimzade, H. & Rezaee, E. D. (2015). The Analysis of Kindergarten Architectural Ideas with a Focus on Play Element. *Fen Bilimleri Dergisi* (CFD), *36* (4), 404–413.

Baczko-Dombi, A., Komendant-Brodowska, A. & Zając, T. (2015). *Lokalne uwarunkowania decyzji edukacyjnych*. In M. Rószkiewicz & K. Saczuk (Eds), Uwarunkowania decyzji edukacyjnych. Wyniki drugiej rundy badania panelowego gospodarstw domowych. Raport tematyczny z badania (pp. 238–293). Warszawa: Instytut Badań Edukacyjnych. Retrieved from: https://www.academia.edu/download/46385498/2015_BACZKO_KOMENDANT_ZAJAC_Raport-Uwarunkowania-decyzji-edukacyjnych-2-runda.pdf [accessed: 09.10.2025].

Blumsztajn, A. (2007). Przykłady rozwiązań edukacji przedszkolnej w krajach członkowskich Unii Europejskiej. In C. Sadowska-Snarska (Ed.), *System instytucjonalnej opieki nad dzieckiem*. Białystok: Wyższa Szkoła Ekonomiczna w Białymstoku.

Chawla, L. (2015). Benefits of nature contact for children. *Journal of Planning Literature*, *30* (4), 433–452.

Gao, J., Wargocki, P. & Wang, Y. (2014) Ventilation System Type, Classroom Environmental Quality and Pupils' Perceptions and Symptoms. *Building and Environment*, *75*, 46–57. https://doi.org/10.1016/j.buildenv.2014.01.015 [accessed: 22.07.2025].

Jung, C., Elsamanoudy, G. & Abdelaziz Mahmoud, N. S. (2025). Towards Safer and Healthier Childcare Facilities: Evaluating Environmental and Safety Standards in Daycare Centers in Dubai. *Buildings*, *15*, 953. https://doi.org/10.3390/buildings15060953 [accessed: 22.07.2025].

Köse, M., Koçyiğit, M., Erdem, C. & Jega, I. (2021). An evaluation of accessibility to preschool education institutions using geographic information systems. *Education and Information Technologies*, *26*, 4307–4328. https://doi.org/10.1007/s10639-021-10482-7

Kurowska, A. & Szczupak, K. (2016). Niedobór czy nadmiar miejsc? Analiza statystyk dostępności opieki żłobkowej w polskich gminach. *Prace Naukowe Uniwersytetu Ekonomicznego we Wrocławiu*, *456*, 86–102. https://doi.org/10.15611/pn.2016.456.06

Lindén, J., Azzouz, M., Stockfelt, L., Gustafsson, M., Molnar, P., Laurelin, M., Rieck Jildén, J., Olofson, H. & Watne, Å. K. (2024). Location, location, location – A study of factors affecting air quality in Swedish preschool yards. *Sustainable Cities and Society*, *113*, 105683. https://doi.org/10.1016/j.scs.2024.105683

Moura e Sa, P. & Saraiva, P. (2001). The development of an ideal kindergarten through concept engineering/quality function deployment. *Total Quality Management*, *12* (3), 365–372. https://doi.org/10.1080/09544120120034500 [accessed: 09.10.2025].

Nedeljkovic, D., Jurenic, T. & Djokic, L. (2023). Comparative analysis of multi-criteria models for decision-making in the process of building adaptation. *Heliyon*, *9*(6). https://doi.org/10.1016/j.heliyon.2023.e16620

Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 6 marca 2025 r. w sprawie ogłoszenia jednolitego tekstu ustawy – Prawo budowlane (Dz.U. 2025 poz. 418). Retrieved from: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20250000418 [accessed: 22.07.2025].

Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 25 maja 2023 r. w sprawie ogłoszenia jednolitego tekstu ustawy o ochronie przyrody (Dz.U. 2023 poz. 1336). Retrieved from: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20230001336 [accessed: 22.07.2025].

Obwieszczenie Ministra Rodziny, Pracy i Polityki Społecznej z dnia 7 grudnia 2018 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Pracy i Polityki Społecznej w sprawie wymagań lokalowych i sanitarnych jakie musi spełniać lokal, w którym ma być prowadzony żłobek lub klub dziecięcy (Dz.U. 2019 poz. 72). Retrieved from: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20190000072 [accessed: 22.07.2025].

Obwieszczenie Ministra Rozwoju i Technologii z dnia 15 kwietnia 2022 r. w sprawie ogłoszenia jednolitego tekstu rozporządzenia Ministra Infrastruktury w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie (Dz.U. 2022 poz. 1225). Retrieved from: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20220001225 [accessed: 22.07.2025].

Palley, H. A. & Usui, C. (2008). Child daycare policy in Japan: an examination of the program and its impacts. *Journal of Comparative Social Welfare*, *24* (2), 165–178. https://doi.org/10.1080/17486830802231156 [accessed: 22.07.2025].

Piętka-Kosińska, K. & Ruzik-Sierdzińska, A. (2010). *Żłobki w Polsce. Badanie empiryczne*. *Badanie przeprowadzone w 2010 r. na zlecenie Banku Światowego przy współpracy merytorycznej*. Warszawa: Departament Polityki Rodzinnej MPiPS. Retrieved from: https://case-research.ecms.pl/pl/zlobki-w-polsce-badanie-empiryczne-i-jakosciowe [accessed: 02.10.2025].

Racław, M. (2024). Wymiary dostępności usług żłobków i klubów dziecięcych: definicje, wskaźniki, wyniki empiryczne. *Polityka Społeczna*, *603* (8), 22–29. https://doi.org/10.5604/01.3001.0054.7545

Ratajczak, K. & Basińska, M. (2021). The Well-Being of Children in Nurseries Does Not Have to Be Expensive: The Real Costs of Maintaining Low Carbon Dioxide Concentrations in Nurseries. *Energies*, *14*, 2035. https://doi.org/10.3390/en14082035

Rozporządzenie Ministra Spraw Wewnętrznych i Administracji z dnia 24 lipca 2009 r. w sprawie przeciwpożarowego zaopatrzenia w wodę oraz dróg pożarowych (Dz.U. 2009 nr 124 poz. 1030). Retrieved from: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20091241030 [accessed: 22.07.2025].

Soga, M., Yamanoi, T., Tsuchiya, K., Koyanagi, T. F. & Kanai, T. (2018). What are the drivers of and barriers to children's direct experiences of nature? *Landscape and Urban Planning*, *180*, 114–120. https://doi.org/10.1016/j.landurbplan.2018.08.015 [accessed: 22.07.2025].

Sungur, M. (2024). Examining preschool education buildings with sustainable architectural approach: Two examples in Konya, Selçuklu. *Journal of Architectural Sciences and Applications*, *9* (1), 277–301. https://doi.org/10.30785/mbud.1382686

Starzyk, A., Donderewicz, M., Rybak-Niedziółka, K., Marchwiński, J., Grochulska-Salak, M., Łacek, P., Mazur, Ł., Voronkova, I. & Vietrova, P. (2023). The Evolution of Multi-Family Housing Development Standards in the Climate Crisis: A Comparative Analysis of Selected Issues. *Buildings*, *13* (8), 1985. https://doi.org/10.3390/buildings13081985 [accessed: 22.07.2025].

Wang, X., Zhao, J., Lu, Y. & Li, X. (2024). Spatial Pattern, Quality Evaluation, and Implications of Preschool Education Facilities in New Urban Areas Using Multi-Source Data: A Case Study from Lingui New District in West China. *Buildings*, *14*, 1718. https://doi.org/10.3390/buildings14061718 [accessed: 22.07.2025].

Amiri, O. (2025). Comparative analysis of the optimal location for a new public nursery: a case study of the Celestynów Commune. *Acta Sci. Pol. Architectura*, *24*, 329–345, DOI: 10.22630/ASPA.2025.24.23

ANALIZA PORÓWNAWCZA OPTYMALNEJ LOKALIZACJI NOWEGO ŻŁOBKA PUBLICZNEGO: STUDIUM PRZYPADKU GMINY CELESTYNÓW

STRESZCZENIE

Niniejszy artykuł przedstawia analizę porównawczą potencjalnych lokalizacji nowego żłobka publicznego w gminie Celestynów. W badaniu zastosowano wielokryterialne podejście do oceny, co umożliwiło zintegrowanie czynników przestrzennych, środowiskowych i społecznych w celu zidentyfikowania optymalnej lokalizacji. Kluczowe aspekty brane pod uwagę to dostępność, bezpieczeństwo, bliskość terenów mieszkalnych oraz warunki środowiskowe, takie jak nasłonecznienie i poziom hałasu. Dzięki analizie na podstawie obserwacji terenowych i zgromadzonych danych wyjściowych uwypuklono korzyści i kompromisy związane z każdą z proponowanych lokalizacji. Wyniki mogą dostarczyć cennych informacji planistom i władzom lokalnym, co pomoże w procesie podejmowania decyzji mającej wpływ na dostępność obiektu oraz bezpieczeństwo i zdrowe środowisko rozwoju dzieci. Niniejsze studium przypadku ilustruje, jak systematyczne analizy przedprojektowe mogą skutecznie wpływać na rozmieszczenie infrastruktury publicznej w małych społecznościach.

Słowa kluczowe: żłobek publiczny, wybór terenu, analiza przestrzenna, planowanie urbanistyczne, rozwój gminy, Celestynów

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REVIEW PAPER

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INNOVATIVE APPROACHES IN SUSTAINABLE ENGINEERING FOCUS ON THE IMPLEMENTATION OF CIRCULAR ECONOMY PRINCIPLES AND THE INTEGRATION OF RENEWABLE ENERGY APPLICATIONS – A REVIEW

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ABSTRACT

This review presents an integrated examination of recent advances in sustainable engineering, linking circular economy strategies, renewable energy applications, and water reuse technologies within a unified framework of resource efficiency. Unlike existing literature that discusses these areas separately, this study synthesises their interrelationships and identifies how combined implementation can accelerate sustainability outcomes. The review assesses current practices in sustainable construction, life cycle assessment, renewable energy deployment, and industrial and municipal water reuse, drawing on case studies from Qatar, the United Arab Emirates and China. Trends, challenges, and research gaps are critically assessed, highlighting the need for large-scale validation, standardised assessment metrics, and supportive regulatory mechanisms. The paper presents a conceptual framework that connects materials, energy, and water efficiency and outlines actionable directions for engineers and researchers to scale sustainable engineering solutions.

Keywords: sustainable engineering, circular economy, renewable energy, life cycle assessment, water reuse

INTRODUCTION

Over the last 20 years, the global market has consistently prioritised energy conservation and the recycling or reuse of water, even before the establishment of criteria such as BREEAM and LEED. An essential aspect of these endeavours has been the implementation of water and energy metering, which involves transferring the accountability and financial burden of consumption to the individual user. Implemented through the use of devices such as hot- and cold-water meters, heat meters, and electricity meters, this strategy has demonstrated its efficacy as an economic method for reducing energy consumption and media usage by decreasing utility bills. Furthermore, there has been a growing acceptance of the principles of the circular economy, which advocate for the reuse of resources. This encompasses the process of reusing treated air in mechanical ventilation and air conditioning systems, collecting rainwater, utilising condensate from cooling systems, and repurposing treated wastewater for activities such as toilet flushing and irrigation of green spaces,

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particularly in hot equatorial areas. This review examines novel methods in sustainable engineering, with a specific emphasis on incorporating circular economy ideas and integrating renewable energy technologies. The text discusses existing techniques, accomplishments, and challenges, offering valuable insights and recommendations for future studies and the development of policies to promote global sustainability. A study by Papadakis, Savvides, Aimilios and Michopoulos (2024) examines the difficulties faced by cities as they develop due to population increase, even in the presence of insufficient mobility infrastructure. They emphasise the need for cities to create sustainable urban mobility plans (SUMPs) in order to tackle this problem. The study provides optimal methods for encouraging a shift in transportation modes by aligning them with public transit policies, promoting active mobility, and discouraging the use of private vehicles.

Maqbool, Arul and Ashfaq (2023) evaluated the level of knowledge among UK practitioners on sustainable construction methods and identified obstacles preventing their implementation. A hybrid methodology was employed, incorporating questionnaire surveys and interviews to gather data from professionals across various fields, as illustrated in Figure 1. The results indicated that professionals in the field possess a higher level of knowledge regarding sustainable practices, with the most prevalent ones being reduce, reuse, and recycle. The primary obstacle was the desire to uphold existing methods rather than the issue of cost. Overcoming these obstacles could enhance the implementation of environmentally friendly building practices in the United Kingdom.

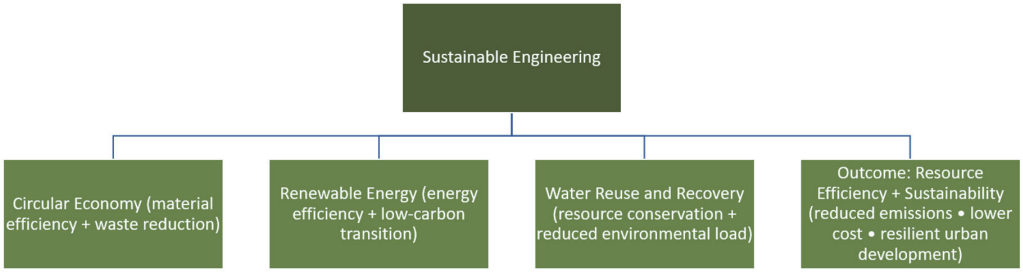


Fig. 1. Integrated framework linking circular economy, renewable energy, and water reuse for sustainable engineering

Source: own work.

Mariyam, Cochrane, Al-Ansari and McKay (2024) developed a techno-policy framework that prioritises sustainable solid waste management in Qatar. The text highlights the significance of private sector training, plastic recycling, and tackling mega-events. The framework also emphasises the necessity of interdisciplinary collaboration, awareness campaigns, and efficient waste management measures. Nevertheless, the absence of complete open data gives rise to difficulties that require focused endeavours in various situations. Hafdhi and Euchi (2023) introduced a novel approach called the multi-attribute superiority, inferiority, and non-inferiority selection approach (MASINISA) to assist consumers in making well-informed choices regarding the selection of renewable energy options in Tunisia. The technique employs comparative measures of superiority, inferiority, and non-inferiority to assess the quality of evidence for the goodness or poverty of a treatment. The suggested MASINISA version was tested at the STEG Company in Tunisia, and all the renewable energy technologies it produced were deemed acceptable by STEG specialists. Duckett, Troldborg, Hendry and Cousin (2024) emphasise the necessity of incorporating climate change and the circular economy into water reuse initiatives in regions like Scotland, where water scarcity is not a significant concern. They propose implementing innovative strategies to overcome obstacles to reuse, such as intricate regulatory

frameworks and trust dependencies. The notion of a 'yum factor' or 'yuck factor' can be employed to facilitate the swift growth of municipal-scale reuse. Despite the rapid growth of studies on sustainable engineering, the existing literature remains fragmented across the circular economy, renewable energy, and water reuse, making it difficult to identify their combined contribution to resource-efficient development. Therefore, this review aims to consolidate recent advancements and critically examine how these three domains complement each other in supporting sustainable engineering practices. The literature used in this review was identified through the Scopus and Web of Science databases, utilising keywords such as 'circular economy', 'renewable energy', 'sustainable construction', 'water reuse' and 'resource efficiency'. Only peer-reviewed articles that were recently published were included to ensure the inclusion of recent insights.

CIRCULAR ECONOMY IN ENGINEERING

The engineering industry prioritises the circular economy, which seeks to reduce waste and enhance resource efficiency by reusing and recycling commodities. This section examines the application of circular economy ideas in several engineering disciplines, with a focus on innovative approaches and successful case studies. The research conducted by Dsilva, Zarmukhambetova and Locke (2023) emphasise the significance of life cycle assessment (LCA) in the building industry for reducing carbon dioxide emissions associated with the production and use of materials. The study, which focused on a G+2 structure in Dubai, found that meticulous material selection and early engagement with LCA resulted in a significant 26% decrease in the building's embodied carbon. The report emphasises the importance of political support in establishing sustainable practices and promoting circularity in the building industry. Pujadas-Gispert et al. (2020) highlight the potential to enhance energy efficiency and reduce the environmental impact of the construction industry. The building envelope plays a crucial role in reducing energy consumption throughout a building's lifespan, as most energy is used during its operation and maintenance. The study assesses the design, construction, and thermal efficiency of a ventilated façade that can be easily installed, disassembled, and packed into containers. The outside structure is constructed using bio-based materials, aligning with the principles of a circular economy. The cladding's outer layer consists of hygiene paper, grass, reeds, recovered textiles, waste from drinking water treatment, bio-based polyester resin, and other miscellaneous components. Temperature and air velocity measurements conducted in Dubai revealed that the façade significantly contributed to preserving cool temperatures within the flat, particularly during the hottest hours of the day. The façade is an attractive option for areas with hot summers and mild winters, as it can reduce energy consumption and lessen the environmental impact of building materials. The study emphasises the importance of the building envelope in implementing sustainable construction practices.

Al Martini et al. (2023) investigated the mechanical properties of concrete mixtures that included recycled concrete aggregate obtained from demolished buildings in Abu Dhabi. The researchers found that concrete with a 20% content of recycled concrete aggregate is appropriate for use in structural applications. Moreover, most ternary blend mixes successfully attained the intended design strength. The research advocates for the broader adoption of root cause analysis in the construction sector. Abu-Hijleh and Jaheen (2019) revealed that the Dubai administration has shown a strong inclination towards integrating sustainable principles across the different phases of construction. This is evident from the introduction of the green building regulations and specification in 2011. This study examines the effectiveness of these limitations and evaluates the benefits of improving the prerequisites to achieve PassivHaus standards, as illustrated in Figure 2. The villa case study at Jumeirah Park was evaluated using the IESVE energy modelling program. The implementation of the updated Dubai green building regulations and specification resulted in reductions in cooling load of 5.9%, 8.7%, 1.6%, 11.0%, and 20.0%, as indicated by the findings. The adoption of PassivHaus standards resulted in a 48% reduction in the cooling load.

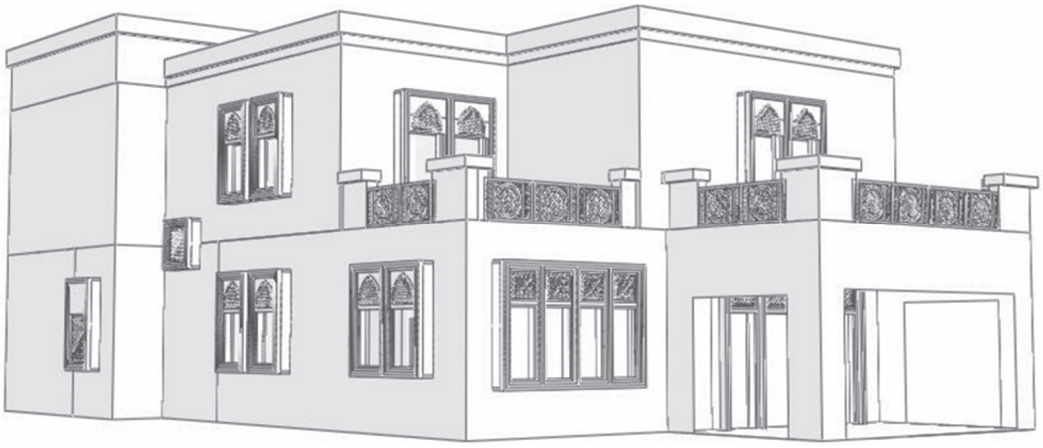


Fig. 2. IESVE villa energy model

Source: Abu-Hijleh and Jaheen (2019).

Obaideen et al. (2021) examine how the growth of the global economy affects the supply of and demand for energy, which in turn influences the creation of sustainable development goals (SDGs). Solar energy has the potential to mitigate energy footprints. The study examines the role of the Mohammed bin Rashid Al Maktoum Solar Park in the United Arab Emirates in advancing the SDGs, with a specific focus on its environmental impact through the implementation of clean and cost-effective energy sources. The park has successfully negated the output of 6.5 million tonnes of carbon dioxide equivalent and accomplished multiple SDGs. Overall, the reviewed studies demonstrate a strong consensus that circular economy strategies significantly reduce embodied carbon and enhance material efficiency in the construction sector. However, while some works highlight bio-based materials and façade systems as major contributors to energy efficiency, others emphasise the recycling of aggregates and the implementation of performance-based regulations. A common research gap is the lack of long-term performance assessments of circular materials under real environmental conditions, along with limited policy frameworks that support large-scale adoption. While circular economy strategies reduce material waste and embodied carbon, their full benefits can only be achieved when supported by clean energy systems. Therefore, the following section examines renewable energy technologies, which play a complementary role in enhancing resource efficiency and reducing the environmental footprint of sustainable engineering projects.

SCOPE AND METHODOLOGY OF THE REVIEW

The objective of this review is to consolidate and critically evaluate recent advancements in sustainable engineering with an emphasis on circular economy strategies, renewable energy applications, and water reuse technologies. The scope of the review encompasses peer-reviewed research articles, case studies, and technical reports that focus on the implementation of sustainable engineering approaches in urban and industrial contexts.

The literature for this review was collected from the Scopus and Web of Science databases using keywords such as ‘circular economy’, ‘sustainable construction’, ‘renewable energy technologies’, ‘water reuse’ and ‘resource efficiency’. Only articles published between 2019 and 2024 were considered to ensure recent developments. The selected studies were analysed based on their objectives, methodologies, outcomes, limitations, and contributions to sustainability, enabling a thematic comparison across the three major domains.

RENEWABLE ENERGY TECHNOLOGIES AND THEIR APPLICATIONS

Renewable energy technologies are crucial in reducing carbon emissions and promoting sustainable development. This section examines the latest advancements and applications of renewable energy, including solar, wind, and bioenergy, as well as their impact on various industries and urban development. Vignisdottir, Barrera-Cardenas and Pascual-Muñoz (2023) examine the growing proportion of electric vehicles and plug-in hybrids in the automotive industry, which necessitates the development of energy centres and charging infrastructure. The use of renewable energy technologies has the potential to make a significant contribution towards achieving low-carbon transportation. Hassan and El-Rayes (2024) devised an innovative multi-objective optimisation framework to enhance the efficiency of building schematic design for the purpose of generating renewable energy on-site. The model prioritises the optimisation of renewable energy generation, the reduction of construction and operational expenses for renewable energy, and the maximisation of the savings-to-investment ratio for integrated renewable energy systems. The model was utilised to enhance the schematic design of a 6,500 m^2 building, emphasising its unique contributions and innovative possibilities.

Chen (2024) investigates the influence of renewable energy technology innovation (RETI) on the urbanisation process in China's prefecture-level cities between 2010 and 2021. The results indicate that RETI plays a key role in promoting urbanisation by enhancing industrial structure, productivity, and rural income. The report presents a conceptual framework and practical suggestions for achieving effective and sustainable urban growth. Although renewable energy reduces the dependence on fossil fuels, urban sustainability also depends on efficient water management. The transition towards circular resource use requires not only low-carbon energy systems but also innovative approaches for water reuse and wastewater recovery, which are examined in the next section.

WATER REUSE AND RESOURCE EFFICIENCY

Water reuse and resource efficiency are essential for addressing water scarcity and enhancing sustainability. This section examines cutting-edge technologies and strategies for reusing water, including desalination and wastewater treatment, to optimise resource efficiency and minimise environmental impact. Lanter et al. (2024) examined the highest possible desalination recovery ratio (RR_{max}) for safely disposing of desalination brine in water-scarce areas such as Kenya. Water samples were collected from the Mara Triangle and analysed to assess contaminant concentrations in relation to established safety thresholds for salinity and hazardous components. The findings indicated that the Mara Triangle had impressive water recoveries, with a maximum ratio of over 94% for agricultural irrigation and 98% for livestock watering. The primary constraint for brine reuse was predominantly salinity, with the boron concentration being the secondary factor. All areas were able to cultivate the most salt-tolerant crops. Amaral, Martins and Dias (2023) emphasise the significance of finding service providers that demonstrate exceptional performance in crucial operational metrics for the long--term viability of the wastewater treatment sector. The study finds Portuguese service providers that excel in wastewater reuse efficiency and examines the key factors that drive their operations. The report suggests promoting the development of smaller service providers to achieve economies of scale and establishing effective infrastructure maintenance methods to support the increasing use of wastewater reuse.

The food industry can achieve sustainable water use by transitioning to circular practices and actively exploring possibilities for water recycling (Harasztiné, Sebestyén & Somogyi, 2024). An illustrative case study was conducted using a chicken processing factory to demonstrate that enhancing wastewater treatment technology can result in a nearly 30% reduction in metal depletion and a 90% decrease in chemical use. Additional mitigation could be accomplished by selecting technical or agricultural reuse alternatives. The study showed an 11.0–17.1% reduction in freshwater consumption and a corresponding decline in metal depletion units –7.6% in 2018 and 2.6% in 2019 – when reusing technology was implemented. Although there are legal

obligations and societal concerns, the study indicates that water reuse is a viable and ecologically responsible option for the food business.

Rodríguez-Castillo et al. (2024) investigate the utilisation of recycled wastewater as a viable solution to mitigate the depletion of freshwater resources. The researchers assess the sustainability of the Anaerobic--Algal Membrane Bioreactor (A2MBR) in Central Chile. The study revealed that the implementation of the A2MBR system resulted in enhanced water supply and nutrient recovery, as well as lowered indicators of global warming, eutrophication, and acidification potential. Furthermore, the treatment costs associated with this system were shown to be competitive when compared to other available solutions. Nevertheless, it is necessary to conduct pilot demonstrations and a comprehensive long-term social assessment in order to verify the validity of these sustainability benefits.

Thomassen et al. (2024) conducted a prospective extended life cycle assessment to compare the environmental impact of a new design of reusable packaging for 2 kg of rice with that of a standard single-use packaging. The study revealed that the reusable rice packaging has the potential to be utilised up to five times. However, it was observed that its influence on global warming and depletion of fossil resources is two to three times greater. The sensitivity analysis identified the reusability and return rate as the most influential parameters. If these parameters could be improved to achieve a value of 99.8%, with a total of 16 uses, the environmental impact of the reusable packaging would be lower than that of its conventional single-use counterpart in terms of climate change. The significant food-to-packaging ratios highlight the need to minimise food waste. Assuming that the packaging design could decrease food losses by 0.2%, the reusable packaging for rice would have a minor impact on water use, mineral resources, and metal resources compared to the single-use packaging for rice. This is true even though the reusable packaging unit itself has a higher environmental impact.

Guleria et al. (2024) investigated the effectiveness of one-pass capacitive electrodialysis on a pilot scale to improve water use and minimise environmental impacts. The study found that one-pass capacitive electrodialysis produced high-quality greenhouse irrigation water, which had decreased Na^+ retention compared to other compounds. The nutrient concentration factors reached their highest values of 2.3 $mg \cdot L^{-1}$, 2.7 $mg \cdot L^{-1}$ and 1.9 $mg \cdot L^{-1}$, respectively. However, there was no significant improvement in ion removal for any of the input compositions at voltages above 12 V and water recovery rates above 80%. The specific energy consumption of one-pass capacitive electrodialysis was one-fourth that of the modelled reverse osmosis system and previous electrodialysis tests. The highest specific energy consumption ever reported for one-pass capacitive electrodialysis was 0.24 $kWh \cdot m^{-3}$.

CASE STUDIES OF SUSTAINABLE ENGINEERING PRACTICES

Case studies offer concrete and practical insights into the implementation of sustainable engineering methods across various geographic regions and industries. This section provides a summary of real-life examples, highlighting the successful application of sustainable practices and showcasing the benefits and challenges encountered in these efforts (Al-Hamrani et al., 2021). The construction sector makes a significant contribution to environmental footprints and the depletion of natural resources. The goals of sustainable construction include minimising waste and having a positive impact on climate change. Qatar's commitment to achieving a sustainable FIFA World Cup in 2022 led to the implementation of an LCA for the Education City Stadium. The study employed the cyclopean concrete method, which involves mixing concrete with stones excavated from the site to construct the stadium's foundation. The cyclopean concrete approach resulted in a 32% decrease in greenhouse gas emissions in comparison to conventional concrete. This indicates that the cyclopean concrete technique can deliver satisfactory structural performance using site-excavated stones as a cost-efficient substitute for conventional aggregates, resulting in a lower environmental footprint. Figure 3 illustrates the application of both bottom-up and top-down techniques in building ecologically friendly structures.

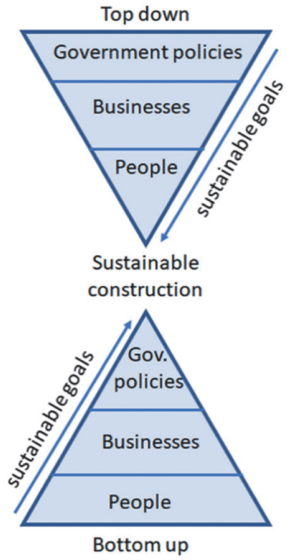


Fig. 3. Utilisation of both top-down and bottom-up methodologies in environmentally friendly construction

Source: Maqbool et al. (2023).

Ahn et al. (2022) performed a comprehensive analysis of the existing literature to find a total of 23 guiding principles that are based on the concept of circular economy in the construction business. The study examined mass timber construction, an environmentally friendly alternative to conventional building materials, and its potential to facilitate the transition towards a low-carbon society. The analysis revealed that although the environmental advantages of mass timber manufacture and building are extensively documented, their potential and circular economy potential are frequently disregarded. There is a lack of evidence and practical examples of prefabricated mass timber panels reaching the end-of-life stage and incorporating circular economy concepts compared to traditional building types. The evaluation identified significant knowledge gaps and urgent research needs for advancing comprehensive strategies in preparing mass timber construction for the circular economy. The results highlight the need to address these deficiencies in the building sector to achieve a more environmentally friendly and circular economy.

Tushar, Mainul Bari and Khan (2022) present a comprehensive multiple-criteria decision-making framework for selecting suppliers in the construction industry with a focus on circular practices. The framework utilises the fuzzy analytical hierarchy process and the preference ranking organisation technique for enriching evaluations (PROMETHEE II) to establish a supplier ranking, with the best-ranked suppliers at the top and the worst-ranked at the bottom. The primary factors for supplier selection include punctual delivery, adherence to specifications, rejection rate, pollution control efforts, utilisation of eco-friendly packaging, and compliance with environmental legislation. This technique is anticipated to strengthen the circular supply chain model and enhance business sustainability.

Wuni and Shen (2022) study circular economy principles in modular construction projects in Hong Kong. Their study employed a range of research approaches, including literature review, consultation, questionnaire survey, mean score ranking, factor analysis, and fuzzy synthetic evaluation, to identify a total of 21 relevant factors. The five primary variables include timely completion of design, strong commitment from the client, effective leadership from the contractor, a team with adequate experience, and a collaborative work environment.

The study also identified three clusters of success factors: streamlined supply chain management, specialised knowledge and early commitment, and collaboration and information management. Torgautov et al. (2022) examined the significant global influence of the building industry on waste generation. The circular economy offers a feasible approach to minimising waste associated with construction and demolition. This study aims to create a framework for strategically developing actions and initiatives that promote environmental consciousness in the construction industry. The technique used by developing economies, such as Kazakhstan, is a balanced scorecard. Key activities include minimising transportation expenses, executing continuous improvement initiatives, overseeing contractor management, accurately forecasting material needs, and facilitating information sharing within the organisation.

Li, Sun, Song, Li and Hao (2021) analyse the sustainability of Rizhao City, a coastal circular economy eco-city, throughout the period from 2005 to 2017. The study found that socioeconomic development's dependence on regional non-renewable resources leads to a larger environmental loading ratio. The circular economy's performance was enhanced with a self-support ratio exceeding 94%. To enhance the sustainability of Rizhao City, further policy recommendations are necessary due to the inadequate coordination within the existing system (Yu et al., 2024).

FUTURE TRENDS AND CHALLENGES IN SUSTAINABLE ENGINEERING

This section examines the emerging patterns and challenges encountered in the field of sustainable engineering. In the pursuit of a more environmentally friendly future, numerous innovative methods and technologies are being examined and implemented. Nevertheless, the journey towards sustainability is filled with challenges that must be addressed to ensure enduring prosperity and global acceptance:

1. The use of circular economy ideas is anticipated to increase, with a specific emphasis on waste reduction and improving resource efficiency. The implementation of recycling technologies and the development of sustainable material design will be essential in effectively reducing resource consumption.
2. The transition to renewable energy sources, such as solar, wind, and biofuels, will continue to gain momentum. To fully harness the potential of renewable energy, it is essential to address the challenges associated with storage, grid integration, and cost reduction.
3. The advancement of intelligent cities that employ data and technology to enhance urban infrastructure will be crucial. The challenges encompass guaranteeing data security, overseeing urban development, and promoting public acceptance and engagement.
4. Advanced water reuse and desalination technologies will play a crucial role in tackling water scarcity. Effectively managing water resources and successfully addressing regulatory and public perception obstacles will be crucial for achieving sustainable water utilisation.
5. Implementing efficient policies and regulations will be crucial in promoting the acceptance and implementation of sustainable practices. Establishing uniform international standards, offering incentives, and ensuring adherence will present notable challenges.

Although technological progress in sustainable engineering is rapid, deployment remains limited by several barriers, including high upfront investment, insufficient policy enforcement, fragmented regulations across regions, and limited public awareness. Moreover, industries are often hesitant to adopt circular and renewable solutions due to uncertainties in long-term performance and a lack of standardised evaluation metrics. To accelerate progress, more substantial government incentives, mandatory reporting of embodied carbon, investment in pilot-scale demonstration projects, and the development of international certifications for circular materials and water-energy recovery systems are urgently needed.

CONCLUSION

This section provides a concise overview of the key discoveries and insights gained from our examination of innovative methods in sustainable engineering, with a particular focus on the importance of circular economy concepts and the integration of renewable energy sources. The evaluated papers provide a comprehensive understanding of current practices and future trends, highlighting both achievements and areas that require further improvement.

1. Our review highlights the need to use circular economy principles in many sectors. Implementing strategies that prioritise resource efficiency and reduce environmental impact is crucial for achieving sustainable development across various sectors, including construction and waste management.
2. The incorporation of sustainable energy technologies, such as solar and wind power, is crucial in decreasing carbon emissions and improving energy sustainability. The studies analysed have demonstrated practical implementations and highlighted the need for ongoing innovation to address current obstacles in this field.
3. Employing LCA approaches in construction and other industries aids in the identification and reduction of environmental impacts. Our review highlights the effectiveness of LCA in reducing carbon emissions associated with products and promoting the use of sustainable materials.
4. Effective water reuse strategies and advanced technology are crucial for tackling water scarcity and enhancing resource efficiency. The evaluated research yields encouraging outcomes in desalination and wastewater treatment, contributing to the implementation of sustainable water management strategies.
5. The results underscore the need for additional investigation and supportive measures to promote the implementation of sustainable practices. To achieve the shift towards sustainable engineering, it is crucial to foster collaboration across multiple disciplines, raise public awareness, and establish robust regulatory frameworks.

To summarise, this research demonstrates substantial advancements in sustainable engineering, while also highlighting the persistent challenges and opportunities for growth. To attain global sustainability goals, it is imperative to continue making efforts in innovation, receiving policy backing, and fostering collaboration. Despite significant progress, current research still lacks large-scale pilot demonstrations and long-term performance assessments of circular materials and integrated energy–water systems. Policymakers should prioritise mandatory embodied-carbon reporting, incentives for integrating renewable energy, and regulatory support for industrial water reuse. Engineers and researchers should focus on developing scalable models that combine material, energy, and water efficiency rather than treating them independently. Coordinated policies, industrial adoption, and interdisciplinary research will be essential for realising the full potential of sustainable engineering.

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Authors' contributions

Conceptualisation: T.B.; methodology: A.S. and T.B.; validation: A.S. and T.B.; formal analysis: A.S., T.B. and W.S.; investigation: A.S. and T.B.; resources: A.S. and T.B.; data curation: A.S. and T.B.; writing – original draft preparation: A.S. and W.S.; writing – review and editing: A.S. and W.S.; visualisation: T.B.; supervision: T.B.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Ahn, N., Dodoo, A., Riggio, M., Muszynski, L., Schimleck, L. & Puettmann, M. (2022). Circular Economy in Mass Timber Construction: State-of-the-Art, Gaps and Pressing Research Needs. *Journal of Building Engineering*, *53*. https://doi.org/10.1016/j.jobe.2022.104562

Al-Hamrani, A., Kim, D., Kucukvar, M. & Cihat Onat, N. (2021). Circular Economy Application for a Green Stadium Construction towards Sustainable FIFA World Cup Qatar 2022. *Environmental Impact Assessment Review*, *87*. https://doi.org/10.1016/j.eiar.2020.106543

Al Martini, S., Sabouni, R., Khartabil, A., Wakjira, T. G. & Alam, M. S. (2023). Development and Strength Prediction of Sustainable Concrete Having Binary and Ternary Cementitious Blends and Incorporating Recycled Aggregates from Demolished UAE Buildings: Experimental and Machine Learning-Based Studies. *Construction and Building Materials*, *380*. https://doi.org/10.1016/j.conbuildmat.2023.131278

Amaral, A. L., Martins, R. & Dias, L. C. (2023). Operational Drivers of Water Reuse Efficiency in Portuguese Wastewater Service Providers. *Utilities Policy*, *83*. https://doi.org/10.1016/j.jup.2023.101591

Abu-Hijleh, B. & Jaheen, N. (2019). Energy and Economic Impact of the New Dubai Municipality Green Building Regulations and Potential Upgrades of the Regulations. *Energy Strategy Reviews*, *24*, 51–67. https://doi.org/10.1016/j.esr.2019.01.004

Chen, S. (2024). Renewable Energy Technology Innovation and Urbanization: Insights from China. *Sustainable Cities and Society*, *102*. https://doi.org/10.1016/j.scs.2024.105241

Dsilva, J., Zarmukhambetova, S. & Locke, J. (2023). Assessment of Building Materials in the Construction Sector: A Case Study Using Life Cycle Assessment Approach to Achieve the Circular Economy. *Heliyon*, *9* (10). https://doi.org/10.1016/j.heliyon.2023.e20404

Duckett, D., Troldborg, M., Hendry, S. & Cousin, H. (2024). Making Waves: Promoting Municipal Water Reuse without a Prevailing Scarcity Driver. *Water Research*, *249*. https://doi.org/10.1016/j.watres.2023.120965

Guleria, T., Broeke, J. van den, Platteau, I., Rijnaarts, T., Alhadidi, A., Gutierrez, L. & Cornelissen, E. (2024). Water Reuse and Resource Recovery from Greenhouse Wastewater by Capacitive Electrodialysis at Pilot Scale. *Desalination*, *583*. https://doi.org/10.1016/j.desal.2024.117669

Hafdhi, S. & Euchi, J. (2023). Designing of New Proposed Technique for the Multi-Attribute Choice Problems: Application to the Selection of Renewable Energy Technologies in the Tunisian Electricity and Gas Society Case Study. *Energy Reports*, *9* (1), 143–159. https://doi.org/10.1016/j.egyr.2022.10.340

Harasztiné, H. R., Sebestyén, V. & Somogyi, V. (2024). Potential Water Reuse Pathways from a Life Cycle Analysis Perspective in the Poultry Industry. *Journal of Water Process Engineering*, *64*. https://doi.org/10.1016/j.jwpe.2024.105577

Hassan, A. A. & El-Rayes, K. (2024). Optimal Use of Renewable Energy Technologies during Building Schematic Design Phase. *Applied Energy*, *353*. https://doi.org/10.1016/j.apenergy.2023.122006

Lanter, A. M., Svetanoff, R., Chitturi, L., Chirchir, A., Moses Nyo Tonglo Arowo, M. N. T., Ringera, H. & Warsinger, D. M. (2024). Maximizing Water Recovery from Reverse Osmosis for Agricultural Brine Reuse in Kenya. *Agricultural Water Management*, *298*. https://doi.org/10.1016/j.agwat.2024.108855

Li, J., Sun, W., Song, H., Li, R. & Hao, J. (2021). Toward the Construction of a Circular Economy Eco-City: An Emergy-Based Sustainability Evaluation of Rizhao City in China. *Sustainable Cities and Society*, *71*. https://doi.org/10.1016/j.scs.2021.102956

Maqbool, R., Arul, T. & Ashfaq, S. (2023). A Mixed-Methods Study of Sustainable Construction Practices in the UK. *Journal of Cleaner Production*, *430*. https://doi.org/10.1016/j.jclepro.2023.139087

Mariyam, S., Cochrane, L., Al-Ansari, T. & McKay, G. (2024). A Framework to Support Localized Solid Waste Management Decision Making: Evidence from Qatar. *Environmental Development*, *50*. https://doi.org/10.1016/j.envdev.2024.100986

Obaideen, K., AlMallahi, M. N., Alami, A. H., Ramadan, M., Abdelkareem, M. A., Shehata, N. & Olabi, A. G. (2021). On the Contribution of Solar Energy to Sustainable Developments Goals: Case Study on Mohammed Bin Rashid Al Maktoum Solar Park. *International Journal of Thermofluids*, *12*. https://doi.org/10.1016/j.ijft.2021.100123

Papadakis, D. M., Savvides, A., Aimilios, M. & Michopoulos, A. (2024). Advancing Sustainable Urban Mobility: Insights from Best Practices and Case Studies. *Fuel Communications*, *20*, 100125. https://doi.org/10.1016/j.jfueco.2024.100125

Pujadas-Gispert, E., Alsailani, Dijk (Koen), K.C.A. van, Rozema (Annine), A. D. K., Hoope (Puck), J. P. ten, Korevaar (Carmen), C. C. & Moonen (Faas), S. P. G. (2020). Design, Construction, and Thermal Performance Evaluation of an Innovative Bio-Based Ventilated Façade. *Frontiers of Architectural Research*, *9* (3), 681–696. https://doi.org/10.1016/j.foar.2020.02.003

Rodríguez-Castillo, M., Balsebre, N., Bolivar-Paypay, V., Poganietz, W-R. & Prieto, A. L. (2024). Sustainability Assessment of a Sequential Anaerobic-Algal Membrane Bioreactor for Wastewater Reuse. *Sustainable Production and Consumption*, *49*, 104–14. https://doi.org/10.1016/j.spc.2024.06.017

Thomassen, G., Peeters, E., Van Hee, N., Noëth, E., Du Bois, E., Boone, L. & Compernolle, T. (2024). The Environmental Impacts of Reusable Rice Packaging: An Extended Comparative Life Cycle Assessment. *Sustainable Production and Consumption*, *45*, 333–347. https://doi.org/10.1016/j.spc.2024.01.014

Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Borucki, C. & Karaca, F. (2022). Performance Assessment of Construction Companies for the Circular Economy: A Balanced Scorecard Approach. *Sustainable Production and Consumption*, *33*, 991–1004. https://doi.org/10.1016/j.spc.2022.08.021

Tushar, Z. N., Mainul Bari, A. B. M. & Khan, M. A. (2022). Circular Supplier Selection in the Construction Industry: A Sustainability Perspective for the Emerging Economies. *Sustainable Manufacturing and Service Economics*, *1*, 100005. https://doi.org/10.1016/j.smse.2022.100005

Vignisdottir, H. R., Barrera-Cardenas, R. & Pascual-Muñoz, P. (2023). Estimation of Environmental Impacts from Renewable Energy Technologies for Application in a Multi-Criteria Decision Model. I*n Transportation Research Procedia*, *72*, 2253–2260. https://doi.org/10.1016/j.trpro.2023.11.714

Wuni, I. Y. & Shen, G. Q. (2022). Developing Critical Success Factors for Integrating Circular Economy into Modular Construction Projects in Hong Kong. *Sustainable Production and Consumption*, *29*, 574–587. https://doi.org/10.1016/j.spc.2021.11.010

Yu, H., Zahidi, I., Chow, M. F., Liang, D. & Øivind Madsen, D. (2024). Reimagining Resources Policy: Synergizing Mining Waste Utilization for Sustainable Construction Practices. *Journal of Cleaner Production*, *464*. https://doi.org/10.1016/j.jclepro.2024.142795

INNOWACYJNE KIERUNKI W INŻYNIERII ZRÓWNOWAŻONEJ Z UWZGLĘDNIENIEM GOSPODARKI O OBIEGU ZAMKNIĘTYM I TECHNOLOGII ODNAWIALNYCH ŹRÓDEŁ ENERGII – PRZEGLĄD

STRESZCZENIE

W niniejszym przeglądzie przeanalizowano nowatorskie strategie w zakresie inżynierii zrównoważonej ze szczególnym uwzględnieniem implementacji koncepcji gospodarki o obiegu zamkniętym i integracji technologii energii odnawialnej. Główne tematy obejmują tworzenie planu zrównoważonej mobilności miejskiej (SUMP), ocenę zrównoważonych metod budownictwa oraz wkład technologii energii odnawialnej w rozwój urbanizacji i zrównoważenia środowiskowego. W artykule omówiono również znaczenie oceny cyklu życia (LCA) w ograniczaniu emisji dwutlenku węgla w budownictwie, wpływ globalnej ekspansji gospodarczej na podaż i popyt na energię oraz potencjał energii słonecznej w osiąganiu celów zrównoważonego rozwoju (SDGs). Ponadto przeanalizowano metody ponownego wykorzystania wody i poprawy efektywności wykorzystania zasobów w przemyśle i gospodarce komunalnej. Studia przypadków przeprowadzonych w Katarze, Zjednoczonych Emiratach Arabskich i Chiny dostarczyły praktycznych spostrzeżeń dotyczących wdrażania tych zrównoważonych metod. W artykule zaprezentowano ramy koncepcyjne łączące efektywne wykorzystanie materiałów, energii i wody oraz określono praktyczne wskazówki dla inżynierów i badaczy dotyczące skalowania zrównoważonych rozwiązań inżynieryjnych.

Słowa kluczowe: inżynieria zrównoważona, gospodarka w obiegu zamkniętym, energia odnawialna, ocena cyklu życia, ponowne wykorzystanie wody

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ORIGINAL PAPER

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DESIGNING FOR WATER AND BEAUTY. THE INFLUENCE OF NATURE-BASED SOLUTIONS AND SUSTAINABLE URBAN DRAINAGE SYSTEMS ON THE AESTHETICS OF ARCHITECTURAL DESIGN OF SELECTED NEIGHBOURHOODS IN FRANCE AND POLAND

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ABSTRACT

The pursuit of healthier and more sustainable cities requires the adoption of nature-based solutions (NBS). In many cases, sustainable urban drainage systems (SUDS) are stipulated by the binding laws. Although they may add some financial burden for maintenance, they enhance the aesthetics of the architectural design. The primary objective of this study is to explore the potential of using SUDS to enhance the aesthetic appeal of architecture and to examine examples of good practice from two selected districts in France and Poland. The benefits of NBS for improved aesthetics and human health are reviewed. The regulatory frameworks are examined, followed by a discussion of the benefits, challenges and circumstances of SUDS. This study presents a comparison of the possibilities of introducing NBS in both countries. The neighbourhoods selected for this study demonstrate that NBS and SUDS may be feasible and improve the aesthetics of entire architectural complexes.

Keywords: nature-based solution, NBS, sustainable urban drainage system, SUDS, aesthetics, architectural design, neighbourhood design, France, Poland

INTRODUCTION

Urbanised areas worldwide face escalating pressures from climate vulnerability, rapid population growth, and the legacy of impervious surfaces that accelerate runoff and flood risk (Intergovernmental Panel on Climate Change [IPCC], 2023). Traditional urban drainage systems (pipes, concrete channels) are often inefficient and contribute to flooding, pollution, and the heat island effect. They are also often hidden or visually unappealing. On the other hand, the use of nature-based solutions (NBS) results in green townscapes, which are human-friendly and visually attractive.

NBS leverage nature and the power of healthy ecosystems to optimise infrastructure and protect people (International Union for Conservation of Nature [IUCN], n.d.). The IUCN defines NBS as 'actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human wellbeing and biodiversity benefits' (Cohen-Shacham, Walters, Janzen & Maginnis, 2016, p. 2). The European Commission (2015) emphasises that NBS work with natural

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processes rather than against them, delivering multiple co-benefits – environmental, social, and economic – simultaneously. Unlike traditional 'grey infrastructure' that serves single purposes, NBS are multifunctional. They can evolve and adapt to changing conditions, providing resilience to climate uncertainty in ways that fixed infrastructure cannot (Frantzeskaki et al., 2019). Moreover, NBS create visible, accessible landscape features that enhance urban aesthetics and provide everyday nature experiences for residents (Raymond et al., 2017).

NBS employed for the management of stormwater are SUDS, also known as green infrastructure or low-impact development. SUDS represent a suite of design strategies, e.g. green roofs, permeable pavements, dry rivers, bioswales, detention basins, etc. that mimic natural hydrologic processes to mitigate stormwater impacts. SUDS reduce the volume and rate of surface water runoff, aim to improve water quality, and help to enhance the biodiversity of the environment (MRMS, 2024). These systems work by infiltrating, storing, and slowly releasing stormwater, mimicking pre-development hydrological conditions while creating opportunities for ecological enhancement and public amenity (Woods Ballard et al., 2015).

While the environmental and economic advantages of SUDS are well documented, their aesthetic contribution has received comparatively less scholarly attention. This research gap is particularly significant given growing recognition that urban aesthetics profoundly influence public health outcomes, social cohesion, and place attachment (Kaplan & Kaplan, 1989; Gehl, 2010). The aesthetic dimension matters for several critical reasons. First, community support for implementing SUDS often depends more on perceived aesthetic quality than technical performance, with the visual appeal influencing political feasibility and maintenance commitment (Apostolaki & Jefferies, 2005). Second, the aesthetic qualities of urban nature – including visual complexity, seasonal variation, and sensory richness – mediate the psychological restoration and stress reduction benefits (Ulrich, 1984; Kaplan, 1995). Third, well-designed SUDS can increase property values and neighbourhood desirability, creating economic arguments for aesthetic investment that complement environmental justifications (Netusil, Levin, Shandas & Hart, 2014). Finally, a SUDS design that resonates with local landscape traditions can strengthen place identity and community pride, contributing to social sustainability (Gobster, Nassauer, Daniel & Fry, 2007).

This study focuses on the aesthetic advantages of integrating SUDS into the urban fabric, with the example of selected neighbourhoods from France and Poland. The primary aim of this research is to examine how NBS and SUDS influence the aesthetic quality of architectural design and contribute to the creation of health-promoting urban environments.

The specific research objectives are:

1. To analyse how regulatory frameworks shape aesthetic outcomes in implementing SUDS in France and Poland, identifying policy instruments and planning mechanisms that enable or constrain design quality.
2. To identify design strategies that successfully integrate SUDS with architectural aesthetics by examining specific technical solutions (green roofs, bioswales, retention ponds, permeable pavements, dry streams) and their visual integration with the built form.
3. To compare cultural approaches to nature-based urban design in French and Polish contexts, exploring how landscape traditions and aesthetic preferences influence the implementation of SUDS and the public perception.
4. To derive practical design recommendations for creating aesthetically successful SUDS that enhance urban liveability and foster community acceptance while meeting functional stormwater management requirements.

This study employs a comparative case study methodology, analysing two neighbourhoods that exemplify successful aesthetic integrations of SUDS: osiedle Pod Brzozami in Warsaw, Poland, and Cité-Jardin in Le Plessis-Robinson, France. These cases were selected based on demonstrated functional success over 10+ years, thoughtful aesthetic design, positive community reception, and contrasting cultural contexts.

The France-Poland comparison is particularly valuable because both countries operate within the European Union regulatory framework on water resource management, providing a common legislative baseline while exhibiting different implementation approaches. France's formal landscape heritage and mature economy contrast with Poland's naturalistic preferences and developing economic context. This enables exploration of how resources, culture, and regulatory maturity influence aesthetic outcomes. Both countries experience temperate climates with comparable hydrological conditions, controlling for environmental variables and ensuring meaningful comparison of design approaches. The authors' familiarity with both contexts, including language proficiency and professional networks, facilitated in-depth data collection and cultural interpretation.

Following this introduction, the paper examines the regulatory frameworks governing NBS and SUDS implementations in France and Poland, exploring how policy shapes design possibilities. The paper then discusses the aesthetic opportunities presented by SUDS, synthesising research on environmental psychology, biophilic design, and therapeutic landscapes. The case study section presents a detailed analysis of both neighbourhoods, followed by a comparative discussion of the findings and practical implications. The conclusion synthesises key insights and offers recommendations for policy, practice, and future research.

REGULATORY FRAMEWORK FOR SUSTAINABLE WATER SOLUTIONS

The implementation of NBS and SUDS in urban environments is increasingly governed by comprehensive regulatory frameworks that mandate their integration into architectural and urban design. France and Poland, two European Union member states, have developed distinct approaches to implementing sustainable water management solutions while also addressing aesthetic considerations in neighbourhood design.

European Union context

The deficit of freshwater is a constant worry for humankind. This is a common problem in France and Poland, as both countries have relatively limited resources of available freshwater (Eurostat data). Both France and Poland operate within the broader European Union regulatory framework, which provides the foundational directives for water management and sustainable urban development. The EU Water Framework Directive (Directive 2000/60/EC) establishes the legal framework for the protection and sustainable use of European waters, while the revised Drinking Water Directive (Directive (EU) 2020/2184) influences national obligations and incentives for water management across member states (Benöhr, 2022). These directives create a harmonised approach to water governance while allowing member states flexibility in implementation methods.

French regulatory framework

France has established a comprehensive legal framework for sustainable water management through successive water laws and basin-scale planning instruments.

The regulatory foundation consists of:

– National water laws (1992 and 2006): These laws introduced and strengthened basin-scale planning and regulatory tools. The 2006 law notably reformed groundwater governance and shifted management approaches, creating a more integrated approach to water resource management (Rinaudo, 2020). These laws establish the legal basis for implementing NBS and SUDS at the local level.
– *Schéma d'Aménagement et de Gestion des Eaux* (SAGE): These basin-level water management plans are produced by local basin commissions and can include opposable regulations – legally enforceable rules against third parties and administrative acts. This provides a direct legal mechanism to require specific water management measures, including NBS and SUDS, at the local scale (Liziard, Barbier & Fernández, 2020).

– Recent policy momentum: The Plan Eau (Water Plan) announced in 2023 signals national intent to accelerate implementation and adapt the regulatory framework to climate pressures while promoting proven solutions, increasing expectations on local authorities to deploy NBS and SUDS (Colas, 2023).

The practical implementation of sustainable water solutions in France operates through a multi-level governance system:
– Local regulatory responsibility: Basin commissions and municipalities draft SAGE-linked regulations and locally adapted rules to achieve plan objectives. This decentralised approach allows for regional adaptation while maintaining national coherence (Liziard et al., 2020).
– Municipal regulatory frameworks: Many local authorities implement regulatory and incentive frameworks to favour sustainable stormwater management. However, experts warn that overly rigid or poorly designed hydrological rules can be counterproductive, advocating for complementary, locally adapted rule sets based on rain-event methods and local objectives (Chocat et al., 2007).
– Basin plans and adaptation programmes: Published by basin agencies, these plans guide priorities including flood risk management, water resource protection, and ecological objectives, thereby shaping which NBS and SUDS measures are prioritised or required in projects (Roy, 2023).
– Technical flexibility: The regulatory approach emphasises a toolbox methodology with multiple solutions and sizes, privileging locally perceived essential objectives and appropriate levels of hydrological solicitation rather than one-size-fits-all prescriptions (Chocat et al., 2022).

When it comes to urban design and aesthetic implications, French regulatory instruments create both constraints and opportunities that influence urban design and neighbourhood architecture:
– Planning constraints on design: SAGE regulations and basin/municipal hydrological rules can impose functional requirements (infiltration, retention, discharge limits) that must be integrated into site layout, green-space distribution, and streetscape design (Liziard et al., 2020).
– Design integration requirements: Integrating SUDS and NBS typically requires architects and urban designers to allocate space for infiltration areas, swales, permeable surfaces, and retention basins while coordinating multi-functionality (public space, ecology, flood control) (Chocat et al., 2022).

In France, there are robust environmental regulations stemming from EU directives, e.g. the EU Water Framework Directive. There is constant pressure for green infrastructure, but implementation varies significantly between regions. In planning permits, aesthetic considerations often come second to functional requirements. Moreover, France's comparatively strong economy enables greater investment in sustainable infrastructure projects, yet cost remains a critical factor, particularly in densely populated urban areas.

Polish regulatory framework

In Poland, similarly to France, the environmental regulations stem from the EU Water Framework Directive. It defines, among other things, environmental objectives for surface waters divided into surface water bodies, e.g., river sections or water reservoirs together with their catchment areas, and for groundwater divided into groundwater bodies (anon, n.d.).

The main legal act in Poland is the Water Law (2001, 2017) and its implementing regulations. In addition to transposing the provisions of the Water Framework Directive, it contains a number of rules indirectly relating to small-scale water retention. One of the objectives of water resource management is to ensure adequate water quantity and quality for the population, protect against floods and droughts, and provide water for agriculture. The implementation of small water retention is, in a sense, the fulfilment of the recommendations of both

the Polish Water Law and the EU Water Framework Directive (Mioduszewski, 2018). The Water Law amended in 2017 contains a number of provisions relating to surface water retention (Ustawa z dnia 20 lipca 2017 r.). Colloquially, these changes to the Water Law are referred to as the 'rain tax' and introduced the obligation to pay fees for reducing natural land retention, i.e., for the so-called discharge of rainwater or meltwater from unsewered areas (Woźniak & Walczkiewicz, 2018).

Strategic documents at the national level that contain references to small retention include: the strategy for the protection of wetlands in Poland (*strategia ochrony obszarów wodno-błotnych w Polsce*), the national environmental policy (*polityka ekologiczna państwa*), the national strategy for the protection and sustainable use of biodiversity (*krajowa strategia ochrony i zrównoważonego użytkowania różnorodności biologicznej*), the rural development programme (*program rozwoju obszarów wiejskich*), the water management strategy (*strategia gospodarki wodnej*), and the draft national water policy until 2030 (*projekt polityki wodnej państwa do roku 2030*). These documents contain direct references to water resources management, including the development of small retention, or protection of wetlands (anon, n.d.).

At the provincial level, the main documents are the provincial small water retention programmes (*wojewódzki program małej retencji*). These programmes include plans for the construction of reservoirs and descriptions of non-technical forms of small water retention. Provisions related to the protection and management of water resources can also be found in provincial and municipal environmental protection programmes.

As in France, many local authorities implement incentive frameworks to favour sustainable stormwater management. At the local level, in places with difficult hydrological conditions, prone to local flooding, the local spatial development plans (*miejscowy plan zagospodarowania przestrzennego*) may stipulate the retention of rainwater within the plot boundaries.

Technical solutions have predominated in the current programmes for developing small-scale water retention in Poland – the main recommendations included the construction of reservoirs for recreational purposes or water supply. In the most recent studies, the researchers emphasise the need to implement non-technical methods: e.g. afforestation, protection of riparian landscape, as well as NBS and SUDS with micro basins. However, there is often no translation of these plans into practical actions (Mioduszewski, 2018).

Poland adheres to EU directives but faces numerous hurdles. Bureaucracy and inconsistencies between various levels of government (national, regional, and local) lead to fragmented planning regulations. The functionality is stipulated, but the aesthetics are not perceived as a priority. There is a need for clear national guidelines specifically addressing the aesthetic aspects of SUDS. Poland's economy is still developing compared to France. The resources available for aesthetic enhancements in SUDS projects may be limited. It is crucial to find cost-effective solutions that balance functionality and aesthetics.

THE AESTHETIC OPPORTUNITY

While the regulatory framework does not prescribe specific aesthetic standards for NBS and SUDS, the functional requirements create design opportunities that can enhance the visual quality of urban environments when properly integrated into architectural concepts. SUDS have the potential to create beautiful and engaging townscapes. This infrastructure can be more than just purely utilitarian. It can enhance urban aesthetics – defined as the visual quality and sensory experience of built spaces. Architectural aesthetics play a pivotal role in shaping human wellbeing, social cohesion, and place identity (Kaplan & Kaplan, 1989; Kaplan, 1995; Gehl, 2010). The integration of NBS and SUDS offers unique opportunities to enrich urban landscapes with dynamic water features and green corridors, thus transforming monotonous streetscapes into vibrant, biophilic environments. However, aesthetics depend on more than simply adding greenery; they require intentional design choices that balance functional performance with visual harmony.

France boasts a long tradition of formal landscape design, which has influenced the history of architecture and urban planning. The principles prioritised a focus on visual order, symmetrical layouts, and grand boulevards. French aesthetics tend towards formality, symmetry, and elegance. There is a long tradition and appreciation for manicured urban green spaces and parks with carefully controlled landscapes. Today, there is a growing movement towards *ville vert* (green city) initiatives, which incorporate nature into the urban fabric. We are facing the process of changing the basic foundation of the presence of nature in the city, and public parks of a new (second) generation (Trojanowska, 2020a). They are places where NBS and SUDS are employed. The park of the new (second) generation is a place where man allows natural rainwater infiltration, soil regeneration, and natural plant succession. The traditional method of garden development and maintenance, horticulture, gives way to a more ecological approach. We can observe that alongside the urban regeneration projects, when eco-neighbourhoods are built, NBS and SUDS are employed. In France, the appreciation for nature is present in a stylised and curated manner. However, the employment of NBS and SUDS requires education and citizen engagement to accept the new, sustainable aesthetics rather than opt for a more formal, symmetric design.

Poland's landscape is shaped by its turbulent history. Heavily destroyed during World War II, the Polish townscape required rapid reconstruction. The post-war reconstruction prioritised functionality and efficiency over aesthetics in many areas. Post-socialist history leaves a lingering legacy of prioritising functionality over beauty. In many neighbourhoods, we can observe utilitarian design with limited aesthetic considerations. Polish aesthetic preferences lean towards naturalistic design that reflects the country's rural heritage. In Poland, there is an appreciation for wilder, more informal landscapes. The strong connection to rural landscapes and vernacular architecture can be leveraged for aesthetically pleasing NBS and SUDS. The desire to reconnect with nature aligns with the potential of aesthetically pleasing SUDS, which can mimic natural ecosystems.

Environmental psychology and landscape aesthetics

There is a plethora of research on the health benefits of contact with nature (Largo-Wight, 2011). The review of research related to urban spaces reveals the importance of maintaining healing gardens, incorporating wooded parks and green space in communities, preserving pristine wilderness, and providing a clear view of nature outside (Largo-Wight, 2011). Recent empirical evidence has significantly strengthened this body of knowledge with a more nuanced understanding of the mechanisms involved.

A comprehensive systematic review by Wu, O'Keefe, Ding and Sullivan (2024) covering studies through 2023 found that while objective biodiversity metrics show mixed links with health outcomes, there is a consistent association between perceived biodiversity and mental health benefits, indicating that perception mediates many nature-health effects. This finding is particularly relevant for SUDS design, as it suggests that creating the perception of biodiversity may be as important as actual ecological diversity.

Large-scale longitudinal studies have provided robust evidence that regular use of green spaces or higher local green-space exposure is associated with better subjective wellbeing and lower psychological distress, with notably stronger protective effects for socioeconomically disadvantaged groups (Galera, Rodriguez, Santos & Martinez, 2025). This equity dimension adds important social justice considerations to landscape design decisions.

Recent experimental work has moved beyond simple 'green versus non-green' comparisons to identify specific spatial features that differentially support psychological restoration. Chen, Liu, Zhang, Wang and Li (2025) used virtual reality and physiological measures to demonstrate that overall area, gently sloped topography, and strategic planting height and strata are key design parameters for stress reduction and attention restoration. These findings provide actionable guidance for practitioners designing therapeutic landscapes.

Not only the green space (i.e. urban parks), but also blue space (i.e. rivers, canals, coast, lakes) received recognition for enhancing health and wellbeing, especially among women (Thomas, 2015). Green and blue spaces are perceived as distinct from the 'grey' urban environment. Growing evidence is documenting 'green'

and 'blue' spaces as 'therapeutic landscapes' (Völker & Kistemann, 2011; Bell, Foley, Houghton, Maddrell & Williams, 2018).

The development of SUDS offers possibilities to create health-promoting places (Trojanowska, 2020b; Trojanowska, 2025). Contact with an aesthetically pleasing green and blue environment may lead to stress reduction and mental regeneration. Recent case studies from Beirut demonstrate how facility quality, sensory plantings, shading, and social nodes in public green spaces are associated with improved mental wellbeing measures, providing evidence-based guidance for place-based improvements (Raad et al., 2025).

Biophilic design

According to the biophilia hypothesis, human beings need contact with nature (Wilson, 1984). Cities that offer the integration of nature into urban design are perceived as healthy and happy places to live (Kellert, Heerwagen & Mador, 2008; Beatley, 2011). Recent research has refined biophilic design theory and moved towards more implementable, evidence-based approaches.

A systematic review by Flores and Soria (2024) synthesised empirical evidence on specific biophilic design parameters, including natural light, materials, vegetation, and sightlines, reporting consistent benefits for productivity, emotional wellbeing, and patient recovery in built settings. However, the review also identified implementation barriers, including cost and technical knowledge gaps that need addressing.

Hung and Chang (2024) found that the holistic application of biophilic principles – particularly security, sensory richness, and integration of natural elements – predicts perceived restorativeness more strongly than any single formal attribute. This supports a systems approach to biophilic design rather than checklist--based implementations.

Innovative machine-learning approaches are now being used to translate perceptual data into concrete design guidance. Zhong and Ren (2024) used gradient boosting trees to predict emotional perceptions of nature-connectedness from landscape metrics, recommending specific compositional guidelines such as optimising the green view index and favouring distant open green spaces with nearby canopy layering to evoke positive emotions.

NBS and SUDS can mimic natural landscapes when cleverly designed. Recent research emphasises moving from pattern lists to quantified design levers (green view index, canopy proximity, mid-level planting, slope gradients) that practitioners can use to tune biophilic interventions for target psychological outcomes. If thoughtfully implemented, these systems offer everyday experiences of contact with nature to urban dwellers, such as views of nature through windows, pocket parks in interior courtyards, or linear parks as part of blue and green infrastructure. SUDS can be designed with native plants to create habitats for wildlife in urban areas while delivering measurable mental health benefits.

Sensory design

The presence of water features and native plants can stimulate all the senses, offering unique experiences. Varied plant colours, textures, and heights create visual interest. The range of dynamic seasonal colours and plant movement interacts with the surrounding architecture.

Apart from visual interest, water features may include fountains or shimmering streams for an auditory experience. The sound of water can be calming and engaging. Current research shows that these multisensory experiences are not merely additive but create emergent perceptual qualities that enhance the overall restorative value of the environment. Recent research has highlighted the critical importance of multisensory presentation of nature. Ha, Kim and Alam (2025) demonstrated that visual-auditory cues work synergistically to enhance restoration, with perceived biodiversity serving as a key mediator. This finding suggests that the sound of water features – whether fountains or shimmering streams – provides more than auditory pleasure; it actively contributes to the perception of ecological richness and subsequent psychological restoration.

Planting also offers tactile and olfactory stimulation. Moreover, edible plants, fruits, and herbs may become a tasty treat. Recent studies emphasise that successful sensory design requires careful attention to seasonal variation, maintenance requirements, and cultural preferences. People may interact with SUDS by walking along swales, crossing bridges, and observing wildlife, with each interaction providing multiple sensory inputs that contribute to the overall therapeutic value of the space.

Emerging research on pocket park design through environmental psychology perspectives (Han & Mamat, 2025) emphasises behavioural criteria that support diverse sensory experiences while ensuring safety and accessibility. This work provides specific guidance for creating small-scale interventions that maximise sensory richness within constrained urban spaces.

Health promotion and placemaking

Aesthetically pleasing SUDS may help to engage people and create a sense of place. Gesler (1996) defined therapeutic landscapes as places where 'physical and built environments, social conditions and human perceptions combine to produce an atmosphere which is conducive to healing'. The term 'health-affirming landscapes' refers to more common everyday places that unite the qualities of therapeutic landscapes to influence people's physical, mental, and spiritual healing (Trojanowska & Sas-Bojarska, 2018).

Recent research has expanded the understanding of how green spaces with SUDS can become health-promoting places. Trojanowska (2025) presents new evidence on therapeutic landscape research in eco-neighbourhood design, demonstrating how systematic integration of ecological and social design principles can create measurably beneficial environments. This work bridges the gap between therapeutic landscape theory and practical urban development.

Contemporary studies reveal two recurrent pathways through which nature delivers health benefits: (a) immediate stress-reduction and affective regulation, and (b) attention restoration and building long-term physical and behavioural capacities (Wu et al., 2024). Understanding these mechanisms allows designers to create interventions targeted at specific health outcomes.

The social and economic impacts of water-sensitive urban design (WSUD) are increasingly recognised as integral to health promotion. Khalaji, Zhang and Sharma (2024) reviewed evidence showing that SUDS and WSUD implementations create not only environmental benefits but also social cohesion, community engagement, and economic value that contribute to overall community wellbeing.

Recent work emphasises the importance of ecological knowledge in the public perception of urban greening. Russo (2025) found that public understanding of native plants' ecological benefits, including their role as larval food plants, significantly affects the acceptance and appreciation of urban green spaces. This suggests that educational components and interpretive design may enhance the health-promoting potential of SUDS installations.

Contemporary research also highlights the need for equitable access to health-promoting landscapes. Studies consistently show stronger protective effects of green space exposure for socioeconomically disadvantaged groups, suggesting that therapeutic landscape design should prioritise environmental justice considerations (Galera et al., 2025).

SUDS DESIGN CHALLENGES AND CIRCUMSTANCES

Implementation of NBS and SUDS may bring some challenges. Using traditional undergroundpipes may be perceived to be much easier in dense urban settings. Moreover, SUDS need a careful aesthetic design to be visually pleasing.

Space constraints

Urban areas often have limited space. SUDS require a large terrain. Some unusual design options, like green retaining roofs, vertical greening, and a combination of underground water tanks and surface urban drainage, may be needed.

Cost and maintenance

SUDS can have higher upfront costs than traditional drainage systems. Moreover, SUDS require ongoing maintenance, e.g. cleaning, pruning, weeding, etc. Even though there are some options to minimise cost, like using native hardy plants and designing for easy access, there is still an additional financial burden on inhabitants. Long-term benefits include reduced flood risk, improved water quality, and increased property values.

Public perception

Some people may be hesitant to accept 'natural' landscapes in urban areas. SUDS offer a dynamic landscape with seasonal plant variations that decay, hibernate during the winter, and are reborn in the spring. People require ecological education to accept a landscape that is not manicured with neatly ordered plants. However, in the long term, the NBS offers not only a healthy place to live but also increases public satisfaction and property values.

CASE STUDIES

In this study, two neighbourhoods with NBS and SUDS were identified as examples of good practices. One is from France and the other is from Poland. They were chosen based on their integration with the architectural context, use of native plant species, and visual complexity. Their aesthetic was highly appreciated by the public and the inhabitants. Both a literature review and study visits were conducted in each of the neighbourhoods presented.

Cité-Jardin, Le Plessis-Robinson, France

Authors: architecture – Maurice-Payret-Dortail, Paul Demay, Jean Festoc (1919–1939); urban renewal and new architecture – François Spoerry (1991–2000); landscape architecture – Diala Haddad (2008)

Project overview

The new Cité-Jardin is located in Le Plessis-Robinson, in the southern suburbs of Paris, France. The project revives the historic idea of the *cité-jardin* (garden city) and adapts it to the needs of a contemporary metropolitan area. The urban tissue is moderately dense and integrates housing blocks, services, and green public spaces. The neighbourhood comprises residential buildings of varied typologies, with commercial and community services located on the ground floors to animate the streetscape. Entrances are organised both from the street and from landscaped interior courtyards.

The main design objective was to combine heritage and innovation: to sustain the symbolic legacy of the early 20th-century garden cities while creating a functional, liveable, and environmentally sustainable neighbourhood. Special attention was given to greenery, water management, and public life to mitigate the nuisances of dense urban living and to foster a strong sense of community (Body & Navarro, 2010).

Design description

The design integrates a variety of SUDS into the urban fabric. Techniques include green roofs, permeable pavements, retention ponds, and bioswales. Water from rooftops and courtyards is collected and channelled into landscaped basins and infiltration areas, which both regulate stormwater runoff and create a pleasant natural setting.

Aesthetic strategies emphasise neo-traditional architecture – with pitched roofs, decorated façades, and arcades – combined with lush greenery, pergolas, and tree-lined pedestrian routes. The courtyards serve as recreational gardens, recalling the historical *cité-jardin* typology while offering modern ecological infrastructure. The design also incorporates references to classical French urbanism, with plazas, avenues, and carefully framed vistas.

Community feedback

Residents have expressed satisfaction with both the aesthetics and liveability of the neighbourhood. The balance of green courtyards and active ground floors has been praised for enhancing social interaction. Several inhabitants noted that the Cité-Jardin feels ‘like a small town within the city’, combining calm and beauty with accessibility to urban services.

In 2005, Le Plessis-Robinson won the European prize for urban flowering. In 2008, Le Plessis Robinson received the Grand Prix Européenne d’Architecture for ‘the reconstruction of the city and the best rebirth of an urban suburb’ (Body & Navarro, 2010).

Lessons learned

Le Plessis-Robinson’s Cité-Jardin demonstrates the value of combining heritage principles with contemporary ecological design. The integration of SUDS into aesthetically appealing courtyards has not only improved stormwater management but also increased property values and residents’ sense of belonging (Figs 1–2). Fifteen years after its completion, the complex remains well-maintained and continues to function as intended.

The project underlines that successful urban regeneration requires both technical solutions and cultural-symbolic dimensions. By reactivating the historic *cité-jardin* model, the designers created a neighbourhood that is ecologically resilient, socially vibrant, and culturally meaningful.

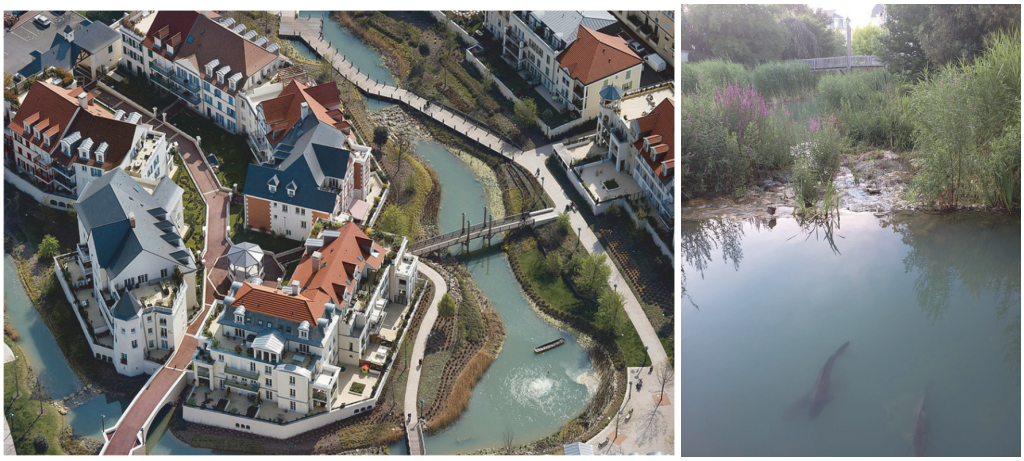


Fig. 1. Cité-Jardin, Le Plessis-Robinson: a one-kilometre artificial river traverses 21 ha of landscaped gardens featuring cascades, gentle slopes, and resting lakes

Source: © Valérie 92700, 2011 (photo on the left); the authors, 2025 (photo on the right).



Fig. 2. Cité-Jardin, Le Plessis-Robinson. The pedestrian path along the nature-based solutions and sustainable urban drainage systems offers a joyful walking experience to visitors and inhabitants

Source: photos by the authors, 2025.

The results from the case study interviews at Le Plessis-Robinson illustrate both the strengths and the limitations of integrating NBS and SUDS into neighbourhood design. On the one hand, the participants expressed a strong appreciation for the aesthetic qualities of the redeveloped landscape. The integration of water, vegetation, and carefully curated public spaces was repeatedly described as 'beautiful', 'charming' and a key factor in their attachment to place. These findings resonate with previous studies that highlight how water-sensitive design contributes not only to environmental resilience but also to cultural heritage and neighbourhood identity.

At the same time, the interviews underline important tensions. Several participants emphasised the fragility of the artificial river system, citing recurrent flooding, technical failures, and costly maintenance. This reflects a recurrent challenge in implementing NBS/SUDS: while their symbolic and aesthetic value is high, their performance depends on long-term management and technical robustness. The perception that 'it is not a real river' suggests that artificiality may weaken residents' trust in the durability of such interventions. Similarly, complaints about overgrown vegetation obscuring water views highlight the importance of maintenance in shaping the aesthetic experience.

Another key dimension is socio-economic. While the redevelopment has led to a remarkable increase in property values – sometimes surpassing Parisian averages – residents noted persistent inequalities between well-maintained apartments and degraded social housing. This demonstrates how the aesthetic and economic gains generated by NBS/SUDS can also reinforce social disparities, a risk that urban design policies must address.

Overall, these findings suggest that designing for water and beauty requires more than technical compliance with environmental regulations. The interviews show that residents value the symbolic and aesthetic presence of water, but they also reveal concerns about costs, fragility, and inequalities.

In this way, the case of Le Plessis-Robinson demonstrates that NBS and SUDS can indeed enhance urban beauty and attachment to place, but only if combined with careful long-term management and social inclusiveness.

Osiedle Pod Brzozami, al. KEN, ul. Płaskowicka, Warsaw, Poland, 2007–2011

Authors: architecture – Marek Budzyński, Zbigniew Badowski, Urszula Lewa; landscape architecture and SUDS – ABIES: Barbara Kraus-Galińska, Monika Wesołkowska, Magdalena Wnęk

Project overview

The neighbourhood is located in the Ursynów District of Warsaw, Poland. It forms part of a relatively dense urban tissue (Fig. 3). The complex houses 290 apartments, with local services and commerce located on the ground floor and accessible from the streets. They were designed to form the city façade, which should enrich the social life of the streets. The entrances to the apartments are located on both sides – the street and the interior courtyard. The interior courtyard is a green oasis with multiple water features designed to collect stormwater – SUDS. The designer's objective was to sustain the biosphere and isolate the inhabitants from the nuisances of city life (Budzyński, n.d.).



Fig. 3. Visualisation of the osiedle Pod Brzozami, Warsaw; view of the complex architecture in an orthoimage

Source: © Marek Budzyński Architekt sp. z o.o. (photo on the left); Google Maps, 2025 (photo on the right).

Design description

The intention was to retain stormwater within the urban complex. SUDS strategies employed are: green retention roofs, surface retention ponds, underground retention ponds, and a system of swales and dry streams. The stormwater from the buildings that have fewer than five levels is conducted via downpipes directly to the 'dry streams' in the recreational garden. The roof over the underground garage serves as a recreational garden. There are bridges over the dry streams, and numerous references to the Japanese gardens tradition (Fig. 4).



Fig. 4. Osiedle Pod Brzozami, Warsaw: view of interior courtyard with water features

Source: photos by the authors, 2025.

Community feedback

The inhabitants of the neighbourhood voiced their satisfaction. One of the inhabitants claimed that it is the most beautiful neighbourhood she has ever seen. The landscape architecture of the neighbourhood sparks admiration among the community. In 2022, this neighbourhood was awarded in the 39th edition of the 'Warszawa w kwiatach [Warsaw in bloom]' competition in the category of urban neighbourhoods – Spółdzielnia Inwestycji Mieszkaniowych Ursynów – osiedle Pod Brzozami I i II; alongside two other neighbourhoods – Wspólnota Mieszkaniowa Żoliborz Kraińskiego; and Robotnicza Spółdzielnia Mieszkaniowa Praga (Praga-Północ) (Zarząd Zieleni m.st. Warszawy, 2022).

Lessons learned

The aesthetics of the pure and clean white façades, almost devoid of any decorations, harmonise with the lush greenery of the interior court recreational garden that is rich in species (Fig. 4). The study visits 15 years after the completion reveal that the system is well-maintained and well-functioning. The employment of SUDS was stipulated by the local binding law. However, the implementation with aesthetic design increased the property value and inhabitants' satisfaction.

The space was limited in Warsaw; therefore, apart from ponds, underground water tanks were used to collect excess stormwater. There is constant maintenance, but the inhabitants claim it is not noticeable. The fact that there are 290 apartments that share the cost of maintenance of the interior courtyard makes the maintenance fees more feasible. All the apartments are privately owned; thus, the costs are balanced by the increase in inhabitants' satisfaction and increased property values.

DISCUSSION

Aesthetic integration as a design imperative

The analysis of both case studies reveals that the aesthetic success of NBS and SUDS extends beyond mere visual appeal to encompass deeper principles of environmental psychology and place attachment. In Warsaw's osiedle Pod Brzozami, the stark contrast between the minimalist white façades and the lush interior courtyard creates what Lynch (1960) termed 'imageability' – a memorable urban form that enhances wayfinding and spatial orientation. This design strategy demonstrates how SUDS can serve as organising elements

in urban composition, providing visual hierarchy and spatial definition that traditional grey infrastructure cannot achieve.

The case of Le Plessis-Robinson illustrates a different but equally effective approach, where SUDS are integrated into a neo-traditional urban fabric that references historical garden city principles while addressing contemporary environmental challenges. The one-kilometre artificial river system functions both as a spine for the neighbourhood's identity and as a practical stormwater management tool. This dual functionality exemplifies what Carmona, Heath, Oc and Tiesdell (2010) describe as 'performative landscapes' – spaces that simultaneously address multiple urban needs through integrated design.

Cultural aesthetics and regional adaptation

The contrasting aesthetic approaches in France and Poland reflect broader cultural attitudes towards nature in urban settings. French formal landscape traditions, rooted in centuries of geometric garden design, manifest in Le Plessis-Robinson's carefully controlled water features and structured plantings. The artificial river, while criticised by some residents for its 'unnaturalness', successfully translates classical French urbanism into contemporary sustainable infrastructure. This approach aligns with what Conan (2000) identifies as the French preference for 'nature cultivated' – natural elements subjected to human ordering principles.

Conversely, the Warsaw project embraces a more naturalistic aesthetic that reflects Polish cultural connections to rural landscapes and vernacular architecture. The dry streams and retention ponds mimic natural hydrological processes while incorporating Japanese garden influences, creating what might be termed a 'hybrid naturalism' that bridges Eastern European landscape preferences with international design vocabularies. This cultural adaptation suggests that successful SUDS implementation requires sensitivity to local aesthetic traditions rather than universal design solutions.

Maintenance as aesthetic practice

Both case studies highlight maintenance as a critical factor in sustaining aesthetic quality over time. The 15-year post-occupancy observations reveal that successful SUDS aesthetics depend on ongoing horticultural practices that balance ecological function with visual appeal. In Warsaw, the shared maintenance costs among 290 apartment owners create a viable economic model for landscape stewardship, while the collective ownership structure ensures consistent care standards.

The experience of Le Plessis-Robinson illustrates both the potential and the challenges of maintaining artificial water systems. Residents' concerns about flooding, technical failures, and overgrown vegetation reveal tensions between ecological succession and aesthetic expectations. This tension reflects what Nassauer (1995) describes as the 'aesthetics of care' – the need for visible human intention in landscape management to maintain public acceptance of ecological design.

The maintenance dimension also reveals important equity considerations. In Le Plessis-Robinson, disparities between well-maintained private areas and the neglected social housing sections demonstrate how aesthetic benefits can become markers of social stratification. This finding suggests that SUDS design must address not only technical performance but also social sustainability and equitable access to environmental amenities.

Regulatory frameworks and design innovation

The comparative analysis of the French and Polish regulatory approaches reveals how policy instruments shape aesthetic outcomes in SUDS implementations. France's mature regulatory system, with its basin-scale planning tools (SAGE) and municipal flexibility, enables more sophisticated integration of aesthetic considerations into functional requirements. The emphasis on 'locally adapted rule sets' (Chocat et al., 2007) allows for design innovation that responds to specific site conditions and cultural preferences.

Poland's evolving framework, while more prescriptive in its functionality requirements, offers opportunities for aesthetic enhancement that remain largely unexploited. The 'rain tax' mechanism creates economic incentives for SUDS adoption but lacks guidance on design quality standards. This regulatory gap suggests that aesthetic considerations require explicit policy attention rather than emerging organically from functional requirements.

The study findings support Ahern's (2013) argument that adaptive planning frameworks are essential for integrating multiple performance criteria in sustainable infrastructure design. Both countries would benefit from regulatory instruments that explicitly address aesthetic standards while maintaining flexibility for local adaptation and design innovation.

Sensory landscapes and therapeutic potential

The multisensory qualities observed in both case studies align with recent research on therapeutic landscape design and environmental psychology. The integration of water sounds, varied plant textures, and seasonal colour changes creates what Ulrich (1984) identified as 'supportive design environments' that promote stress reduction and psychological restoration. In Warsaw, the bridges over dry streams provide opportunities for contemplative movement through the landscape, while in Le Plessis-Robinson, the linear river system creates extended walking experiences that encourage physical activity and social interaction.

The wildlife habitats created by native plantings in both projects contribute to what Fuller, Irvine, Devine-Wright, Warren and Gaston (2007) term 'everyday nature experiences' that support urban biodiversity while enhancing residents' sense of connection to natural systems. These findings support the growing recognition that urban SUDS can serve as stepping stones in metropolitan ecological networks while providing immediate benefits for human health and wellbeing.

However, the study also reveals challenges in the public perception of dynamic, seasonal landscapes. Residents' preferences for 'manicured' appearances over ecological succession highlight the need for educational initiatives that help communities understand and appreciate the aesthetic qualities of naturalistic urban landscapes. This educational dimension is crucial for the long-term success of SUDS as aesthetic interventions.

Economic dimensions of aesthetic investment

Both case studies demonstrate positive relationships between the aesthetics of SUDS and property values, supporting the economic case for investing in design quality. The Warsaw project's sustained market performance 15 years post-completion suggests that well-designed SUDS create lasting value that justifies the initial aesthetic investments. Similarly, Le Plessis-Robinson's property values exceeding Parisian averages indicates that suburban locations can compete with urban centres when enhanced by high-quality environmental design.

These economic benefits extend beyond individual property values to encompass broader neighbourhood transformation. The award recognition received by both projects – Warsaw's 'Warszawa w kwiatach' competition and Le Plessis-Robinson's European prizes – demonstrates how aesthetic excellence in SUDS design contributes to civic pride and regional competitiveness.

However, the economic success of these projects also raises questions about affordability and social accessibility. The gentrification pressures evident in Le Plessis-Robinson suggest that aesthetic enhancement through SUDS may contribute to displacement of lower-income residents. This finding highlights the need for inclusive design strategies that distribute aesthetic and environmental benefits equitably across diverse communities.

Limitations and methodological considerations

The study's focus on successful examples provides valuable insights into best practices but may not fully capture the challenges and failures that characterise many SUDS implementations. The selection criteria emphasising 'high aesthetic appreciation' potentially introduce a bias towards projects with exceptional design resources and maintenance capabilities. Future research should examine a broader range of SUDS projects, including those with more modest budgets and less favourable site conditions.

The temporal dimension of aesthetic perception also requires further investigation. While both case studies demonstrate sustained aesthetic appeal over 15+ years, longer-term studies are needed to understand how SUDS aesthetics evolve with climate change, urban densification, and changing cultural preferences. The maintenance challenges observed in Le Plessis-Robinson suggest that aesthetic sustainability may require different strategies than ecological sustainability.

The study's European context also limits its generalisability to other climate zones and cultural contexts. The temperate climate conditions and specific regulatory frameworks in France and Poland may not translate directly to tropical, arid, or arctic urban environments, where different SUDS technologies and aesthetic approaches may be more appropriate.

Implications for design practice

The findings suggest several important considerations for practitioners designing SUDS in urban contexts. First, aesthetic integration must be considered from project inception rather than added as a superficial enhancement. Both successful case studies demonstrate how water management requirements can become organising principles for overall site design, creating coherent landscape narratives that enhance rather than compromise architectural concepts.

Second, the cultural dimension of aesthetic preference requires careful attention to local contexts and traditions. The contrasting approaches in France and Poland suggest that successful SUDS aesthetics emerge from dialogue between universal ecological principles and specific cultural landscapes. This finding supports calls for more participatory design processes that engage communities in defining aesthetic criteria for sustainable infrastructure.

Third, the maintenance dimension requires integration into project planning and financing from the outset. The economic models demonstrated in both case studies – shared ownership costs in Warsaw and municipal investment in Le Plessis-Robinson – provide templates for sustaining aesthetic quality over time. However, these models may require adaptation for different ownership structures and economic contexts.

Finally, the educational dimension emerges as being crucial for public acceptance of naturalistic urban landscapes. Both projects succeeded partly because residents developed an understanding and appreciation for ecological processes and seasonal change. This suggests that SUDS design should incorporate interpretive elements and community engagement strategies that build ecological literacy alongside aesthetic appreciation.

CONCLUSIONS

This study has demonstrated that NBS and SUDS represent far more than functional infrastructure – they constitute powerful tools for enhancing urban aesthetics and creating health-promoting environments. Through the comparative analysis of selected neighbourhoods in France and Poland, this research reveals how regulatory frameworks can successfully mandate sustainable water management while simultaneously fostering beautiful, liveable urban spaces.

Key findings

The case studies from Warsaw's osiedle Pod Brzozami and Le Plessis-Robinson's Cité-Jardin provide compelling evidence that well-designed SUDS can transform urban neighbourhoods into aesthetically pleasing, biophilic environments. Both projects successfully integrate water management with landscape architecture, creating dynamic water features that serve multiple functions: environmental resilience, sensory stimulation, and community gathering spaces. The positive feedback from residents in both locations underscores the importance of aesthetic considerations in sustainable urban design.

The regulatory analysis reveals that while France and Poland operate within the same EU framework, their implementation approaches differ significantly. France's more mature regulatory system and stronger economy enable greater investment in aesthetic enhancements, while Poland's developing framework prioritises functionality over beauty. However, both countries demonstrate that legal requirements for SUDS can be successfully implemented without compromising – and often enhancing – neighbourhood aesthetics.

Theoretical contributions

This research contributes to the growing body of knowledge on therapeutic landscapes and biophilic design by demonstrating how SUDS can serve as everyday interventions for urban health promotion. The study supports recent findings that perceived biodiversity and multisensory experiences of nature are crucial mediators of psychological restoration. By integrating water features, native plantings, and carefully designed pedestrian pathways, SUDS create opportunities for regular contact with nature that benefit mental health and social cohesion.

The aesthetic dimension of SUDS emerges as particularly important for public acceptance and long-term success. The study shows that residents value not only the environmental benefits but also the symbolic and cultural meanings of water in urban spaces. This finding challenges purely utilitarian approaches to sustainable infrastructure and argues for design strategies that address both functional and experiential qualities.

Practical implications

For urban planners and architects, this research provides evidence that aesthetic considerations should be integral to SUDS design from the outset, not treated as secondary enhancements. The success of both case studies demonstrates that investing in landscape architecture and maintenance creates long-term value through increased property values, resident satisfaction, and community pride.

Design recommendations for practitioners

Based on the comparative analysis, several practical guidelines emerge for creating aesthetically successful SUDS:

1. Plan aesthetics from inception: Do not add landscape design after the engineering is done. Visual quality, sensory experience, and spatial planning need to be part of the initial concept, not afterthoughts.
2. Align with cultural landscape traditions: The design approaches should match local aesthetic preferences. Formal French garden traditions work in France; naturalistic approaches resonate in Poland. Importing foreign design languages without considering local culture risks rejection by residents.
3. Design for multisensory experience: Think beyond visual appeal. The sound of flowing water, the scent of flowering plants, the texture of different surfaces – these sensory qualities make SUDS spaces memorable and restorative.
4. Ensure universal accessibility: SUDS spaces need smooth pathways, gentle slopes, rest areas, and multiple access points. They should work for all residents regardless of age, mobility, or socioeconomic status.

5. Plan for long-term maintenance: Set up adequate maintenance budgets and protocols from the start. Without ongoing care, even beautifully designed systems deteriorate. Both functional performance and aesthetic appeal depend on regular maintenance.
6. Foster social interaction: Include benches, gathering spaces, and pathways that encourage community use. Water management infrastructure should double as valued neighbourhood amenities where people actually want to spend time.
7. Educate residents: Many people need help in understanding naturalistic landscapes. Interpretive signage and community programming can build appreciation for ecological processes, seasonal changes, and the wildlife these systems support.

Social justice and inclusiveness

NBS and SUDS increase the accessibility of urban green spaces and promote inclusiveness and social justice. As they improve the microclimate, they mitigate the effect of urban heat islands and may serve as a good example of adaptation to climate change in large cities.

However, attention must be paid to the equitable distribution of high-quality SUDS across all neighbourhoods, not just affluent areas. The case studies demonstrate that aesthetically pleasing SUDS are achievable even in moderate-income social housing contexts, challenging assumptions that design quality is a luxury only wealthy communities can afford. Design processes should involve diverse community members to ensure SUDS serve as public goods accessible to all residents, avoiding patterns where sustainable infrastructure accelerates gentrification or creates exclusive enclaves.

Climate change adaptation

The findings take on particular urgency in the context of climate change. Urban areas worldwide face increasing challenges from extreme weather events – intense rainfall, prolonged droughts, and heat waves. SUDS are no longer optional amenities, but essential infrastructure for climate adaptation.

Both case studies demonstrate how SUDS contribute to climate resilience: managing stormwater during increasingly frequent heavy rainfall events, reducing local temperatures during heat waves through vegetation and water features, maintaining landscape function during dry periods through water retention and native plantings, and supporting biodiversity as species adapt to changing conditions. The aesthetic dimension becomes critical for ensuring public acceptance and long-term political support for the large-scale SUDS networks cities need to implement for climate adaptation.

Looking forward, climate projections suggest that temperate European cities will experience more Mediterranean-like conditions: hotter, drier summers punctuated by intense rainfall events. SUDS designed for these future conditions must be both resilient and attractive, supporting human and ecological communities through significant environmental change.

The study also highlights the importance of education and community engagement in fostering acceptance of ‘naturalistic’ urban landscapes. As cities transition from formal, manicured green spaces to more ecological approaches, residents need support in understanding and appreciating seasonal variations, natural plant succession, and wildlife habitats.

Limitations and future research

This study’s focus on European contexts and temperate climate zones limits the generalisability of the findings to other geographic and cultural contexts. Future research should explore how aesthetic preferences for NBS and SUDS vary across different cultural traditions and environmental conditions. Longitudinal studies tracking the aesthetic and functional performance of SUDS over extended periods would also provide valuable insights into design durability and maintenance requirements.

The socio-economic dimensions revealed in the Le Plessis-Robinson case study warrant further investigation. While SUDS can increase property values and neighbourhood attractiveness, they may also contribute to gentrification and social displacement. Future research should examine how to design inclusive NBS that benefit all residents rather than exacerbating urban inequalities.

The study's focus on successful examples, while useful for identifying best practices, limits the understanding of what causes SUDS projects to fail aesthetically. Future research examining less successful implementations would reveal important barriers and pitfalls to avoid.

Policy recommendations

Based on these findings, several policy recommendations emerge:

1. Integrate aesthetic standards into SUDS regulations: Planning authorities need design guidelines that address visual quality, sensory experience, and cultural appropriateness – not just technical performance. Regulations should require aesthetic considerations from the start, not treat them as optional extras.
2. Develop regional design manuals: Generic guidelines do not work. Cities need context-specific manuals featuring local best practices, native plant palettes, and design approaches that resonate with local culture. This would help ensure consistent quality across different projects.
3. Invest in long-term maintenance: SUDS need ongoing care to stay both functional and attractive. Funding mechanisms should cover lifecycle costs, not just installation. Without maintenance budgets, even well-designed systems become neglected eyesores.
4. Promote community education: Many residents need help in understanding and appreciating naturalistic landscapes. Interpretive signage, community workshops, and educational programming can build an appreciation for ecological processes, seasonal changes, and the wildlife habitats these systems support.
5. Ensure equitable distribution: High-quality SUDS should not be concentrated in affluent neighbourhoods while lower-income areas get only basic functionality. Policies should mandate good design across all communities, making beautiful, effective water management a right, not a luxury.
6. Include aesthetic performance metrics: Current SUDS evaluation focuses on technical criteria like water infiltration and pollutant removal. This is not enough. Aesthetic quality, user satisfaction, and social benefits should also be measured to complete the picture of how well these systems perform.

Final reflections

The transformation of urban drainage from hidden, purely functional infrastructure into visible, aesthetically pleasing landscape features represents a fundamental shift in how cities can integrate sustainability and beauty. The examples from Warsaw and Le Plessis-Robinson demonstrate that this integration is not only possible but highly beneficial for urban communities.

As cities worldwide grapple with climate change, urbanisation pressures, and public health challenges, the aesthetic dimension of sustainable infrastructure becomes increasingly important. Beautiful, well-functioning SUDS can serve as catalysts for broader urban transformation, creating neighbourhoods that are simultaneously resilient, healthy, and delightful to inhabit.

The evidence presented in this study suggests that designing for water and beauty is not a luxury but a necessity for creating truly sustainable cities. By embracing the aesthetic potential of NBS and SUDS, urban designers can craft environments that nourish both ecological and human wellbeing, fostering the kind of places where communities thrive in harmony with natural systems.

Future urban development must move beyond the false dichotomy between functionality and beauty, recognising that the most successful sustainable infrastructure serves multiple purposes: environmental protection, human health, social cohesion, and aesthetic delight. The neighbourhoods examined in this study point towards a future where water management becomes an art form, where water systems double

as community amenities, and where the practical necessity of climate adaptation creates opportunities for urban beauty.

In this vision, every rain garden becomes a pocket of biodiversity, every bioswale a linear park, and every retention pond a focal point for neighbourhood identity. The path forward requires continued collaboration between architects, engineers, landscape architects, urban planners, and communities to realise the full potential of designing for water and beauty in our rapidly changing urban world.

Authors' contributions

Conceptualisation: M.T. and M.H.T.; methodology: M.T. and M.H.T.; validation: M.T. and M.H.T.; formal analysis: M.T. and M.H.T.; investigation: M.T. and M.H.T.; resources: M.T. and M.H.T.; data curation: M.T. and M.H.T.; writing – original draft preparation: M.T. and M.H.T.; writing – review and editing: M.T. and M.H.T.; visualisation: M.T. and M.H.T.; supervision: M.T. and M.H.T.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Ahern, J. (2013). Urban landscape sustainability and resilience: The promise and challenges of integrating ecology with urban planning and design. *Landscape Ecology*, *28* (6), 1203–1212.

anon (n.d.). *Mała retencja w praktyce, w aktach prawnych i dokumentach strategicznych*. Retrieved from: http://www.malaretencja.pl/images/platforma_ed/lekcje/Lekcja_maa__retencja_w_aktach_prawnych.pdf [accessed: 25.09.2025].

Apostolaki, S. & Jefferies, C. (2005). *Social impacts of stormwater management techniques including river management and SUDS* (Final report, SUDS01). Edinburgh: SNIFFER.

Beatley, T. (Ed.). (2011). *Biophilic cities: Integrating nature into urban design and planning*. Washington, D.C.: Island Press.

Bell, S. L., Foley, R., Houghton, F., Maddrell, A. & Williams, A. M. (2018). From therapeutic landscapes to healthy spaces, places and practices: A scoping review. *Social Science & Medicine*, *196*, 123–130. https://doi.org/10.1016/j.socscimed.2017.11.035

Benöhr, I. (2022). The Right to Water and Sustainable Consumption in EU Law. *Journal of Consumer Policy*, *46*, 53–77. https://doi.org/10.1007/s10603-022-09532-5

Body, C. & Navarro, L. (2010). *Cité-jardin du Plessis-Robinson*. *Annexe: Cité Jardin*. Retrieved from: http://thomas.guillard.free.fr/citejardin/index.php?onglet=annexe [accessed: 25.09.2025].

Budzyński, M. (n.d.). *„Pod Brzozami" przy al. KEN w Warszawie*. Retrieved from: http://mbarch.pl/pod-brzozami-przy-ul-ken-w-warszawie/ [accessed: 25.09.2025].

Carmona, M., Heath, T., Oc, T. & Tiesdell, S. (2010). *Public places, urban spaces: The dimensions of urban design* (2nd ed.). New York: Architectural Press.

Chen, H., Liu, Y., Zhang, L., Wang, X. & Li, M. (2025). Mechanisms linking urban plant landscape spatial characteristics to stress regulation and attention recovery. *Land Degradation & Development*, *36* (2), 445–462. https://doi.org/10.1002/ldr.70114

Chocat, B., Afrit, B., Maytraud, T., Savary, P. & Tedoldi, D. (2022). Comment mettre en place des règles hydrologiques efficaces pour la gestion durable des eaux pluviales urbaines. *Techniques. Sciences. M*éthodes, *10*, 39–62. https://doi.org/10.36904/tsm/202210039

Chocat, B., Ashley, R., Marsalek, J., Matos, M. R., Rauch, W., Schilling, W. & Urbonas, B. (2007). Toward the Sustainable Management of Urban Storm-Water. *Indoor and Built Environment*, *16* (3), 273–285. https://doi.org/10.1177/1420326X07078854

Cohen-Shacham, E., Walters, G., Janzen, C. & Maginnis, S. (Eds). (2016). *Nature-based solutions to address global societal challenges*. Gland: IUCN.

Colas, A. (2023). Face aux défis de l'eau, accélérer sur les solutions n'est plus une option. *Annales des Mines – Responsabilité & environnement*, *4* (112), 59–63. https://doi.org/10.3917/re1.112.0059

Conan, M. (2000). *Environmentalism and landscape architecture*. Dumbarton Oaks: Dumbarton Oaks Research Library and Collection.

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. OJ L 327, 22.12.2000, pp. 1–73.

Directive (EU) 2020/2184 of the European Parliament and of the Council of 16 December 2020 on the quality of water intended for human consumption (recast) (Text with EEA relevance). OJ L 435, 23.12.2020, pp. 1–62.

European Commission (2015). *Towards an EU research and innovation policy agenda for nature-based solutions & re-naturing cities*. Publications Office. https://data.europa.eu/doi/10.2777/479582

Flores, C. & Soria, E. A. (2024). Examinando el diseño biofílico: Una revisión sistemática a sus parámetros y su impacto en el bienestar de las personas. *Arquitek*, *26* (1), 12–28. https://doi.org/10.47796/ra.2024i26.1046

Frantzeskaki, N., McPhearson, T., Collier, M. J., Kendal, D., Bulkeley, H., Dumitru, A., Walsh, C., Noble, K., Wyk E. van, Ordóñez, C., Oke, C. & Pintér, L. (2019). Nature-based solutions for urban climate change adaptation: Linking science, policy, and practice communities for evidence-based decision-making. *BioScience*, *69* (6), 455–466.

Fuller, R. A., Irvine, K. N., Devine-Wright, P., Warren, P. H. & Gaston, K. J. (2007). Psychological benefits of greenspace increase with biodiversity. *Biology Letters*, *3* (4), 390–394.

Galera, M., Rodriguez, P., Santos, L. & Martinez, A. (2025). Neighborhood green space and psychological distress: A longitudinal study of socioeconomic disparities in mental health outcomes. *Environment International*, *195*, 109799. https://doi.org/10.1016/j.envint.2025.109799

Gehl, J. (with Rogers, L. R.). (2010). *Cities for people*. Washington, D.C.: Island Press.

Gesler, W. (1996). Lourdes: Healing in a place of pilgrimage. *Health & Place*, *2* (2), 95–105. https://doi.org/10.1016/1353-8292(96)00004-4

Gobster, P. H., Nassauer, J. I., Daniel, T. C. & Fry, G. (2007). The shared landscape: What does aesthetics have to do with ecology? *Landscape Ecology*, *22* (7), 959–972.

Google Maps (2025). Retrieved from: https://maps.google.com [accessed: 25.09.2025].

Ha, J., Kim, H. J. & Alam, M. M. L. (2025). Linking visual–auditory cues to restoration: The mediating role of perceived biodiversity. *International Journal of Environmental Research and Public Health*, *22* (8), 1267. https://doi.org/10.3390/ijerph22081267

Han, D-W. & Mamat, M. (2025). Behavioral criteria in pocket park design through the lens of environmental psychology: A systematic review. *Environment & Social Psychology*, *10* (6), 3818. https://doi.org/10.59429/esp.v10i6.3818

Hung, S-H. & Chang, C-Y. (2024). Designing for harmony in urban green space: Linking the concepts of biophilic design, environmental Qi, restorative environment, and landscape preference. *Journal of Environmental Psychology*, *98*, 102294. https://doi.org/10.1016/j.jenvp.2024.102294

Intergovernmental Panel on Climate Change [IPCC]. (2023). *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed.). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781009325844

International Union for Conservation of Nature and Natural Resources [IUCN]. (n.d.). *Nature-based Solutions.* Retrieved from: https://iucn.org/our-work/nature-based-solutions [accessed: 25.09.2025].

Kaplan, S. (1995). The restorative benefits of nature: Toward an integrative framework. *Journal of Environmental Psychology*, *15* (3), 169–182. https://doi.org/10.1016/0272-4944(95)90001-2

Kaplan, R. & Kaplan, S. (1989). *The experience of nature: A psychological perspective* (s. xii, 340). Cambridge: Cambridge University Press.

Kellert, S. R., Heerwagen, J. H. & Mador, M. L. (Ed.). (2008). *Biophilic design: The theory, science, and practice of bringing buildings to life*. Hoboken, NJ: Wiley.

Khalaji, F., Zhang, J. & Sharma, A. (2024). Social and economic impacts of water sensitive urban design: A review. *Water*, *17* (1), 16. https://doi.org/10.3390/w17010016

Largo-Wight, E. (2011). Cultivating healthy places and communities: Evidenced-based nature contact recommendations. *International Journal of Environmental Health Research*, *21* (1), 41–61. https://doi.org/10.1080/09603123.2010.499452

Liziard, S., Barbier, R. & Fernández, S. (2020). Réglementer au plus près des territoires: le cas de la ressource en eau en France. *VERTIGO*. https://doi.org/10.4000/VERTIGO.28057

Lynch, K. (1960). *The image of the city*. Cambridge: MIT Press.

Mioduszewski, W. (2018). Mała retencja elementem gospodarki wodnej. In *Współczesne problemy retencji wód*. Warszawa: Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy.

MRMS. (2024, 30 April). *The Natural Approach: Sustainable Drainage Systems (SuDS)*. Retrieved from: https://mrms.co.uk/the-natural-approach-sustainable-drainage-systems-suds/ [accessed: 25.09.2025].

Nassauer, J. I. (1995). Messy ecosystems, orderly frames. *Landscape Journal*, *14* (2), 161–170.

Netusil, N. R., Levin, Z., Shandas, V. & Hart, T. (2014). Valuing green infrastructure in Portland, Oregon. *Landscape and Urban Planning*, *124*, 14–21.

Raad, M., Kallas, G., As-sadi, F., Zeidan, N., Dawalibi, V. & Russo, A. (2025). From research to design: Enhancing mental well-being through quality public green spaces in Beirut. *Land*, *14* (8), 1558. https://doi.org/10.3390/land14081558

Raymond, C. M., Frantzeskaki, N., Kabisch, N., Berry, P., Breil, M., Nita, M. R., Geneletti, D. & Calfapietra, C. (2017). A framework for assessing and implementing the co-benefits of nature-based solutions in urban areas. *Environmental Science & Policy*, *77*, 15–24.

Rinaudo, J-D. (2020). Groundwater Policy in France: From Private to Collective Management. In J. D. Rinaudo, C. Holley, S. Barnett, M. Montginoul (Eds), *Sustainable Groundwater Management* (pp. 47–65). Cham: Springer. https://doi.org/10.1007/978-3-030-32766-8_3

Roy, L. (2023). L'action des instances de bassin, l'exemple du bassin Rhône-Méditerranée. *Annales des Mines – Responsabilité & environnement*, *4* (112), 37–41. https://doi.org/10.3917/re1.112.0037

Russo, A. (2025). Beyond beauty: Exploring how knowledge of larval food plants and ecological benefits affects public perception of native and non-native plants in urban greening. *Urban Ecosystems*, *28* (3), 1796–1812. https://doi.org/10.1007/s11252-025-01796-2

Thomas, F. (2015). The role of natural environments within women's everyday health and wellbeing in Copenhagen, Denmark. *Health & Place*, *35*, 187–195. https://doi.org/10.1016/j.healthplace.2014.11.005

Trojanowska, M. (2020a). The new generation of urban parks and health-promoting landscapes in eco-neighborhoods. *Technical Transactions*, *117* (1), 1–14. https://doi.org/10.37705/TechTrans/e2020003

Trojanowska, M. (2020b). Health-Promoting Places: Rain Gardens and Sustainable Water Management. *IOP Conference Series: Materials Science and Engineering*, *960* (2), 022025. https://doi.org/10.1088/1757-899X/960/2/022025

Trojanowska, M. (2025). Therapeutic landscape research evidence in eco-neighbourhood design. In *Sustainable Urban Design* (pp. 145–168). Routledge. https://doi.org/10.4324/9781003494898

Trojanowska, M. & Sas-Bojarska, A. (2018). Health-Affirming Everyday Landscapes in Sustainable City. Theories and Tools. *Architecture, Civil Engineering, Environment*, *11* (3), 41–52. https://doi.org/10.21307/acee-2018-037

Ulrich, R. (1984). View through a window may influence recovery from surgery. *Science*, *224* (4647), 420–421.

Ustawa z dnia 20 lipca 2017 r. – Prawo wodne. Dz.U. 2017 poz. 1566.

Valérie 92700 (2011, 6 February). *0410OR06112071 – Le Plessis Robinson*. Retrieved from: https://www.flickr.com/photos/27702413@N00/5421321756 [accessed: 25.09.2025].

Völker, S. & Kistemann, T. (2011). The impact of blue space on human health and well-being – Salutogenetic health effects of inland surface waters: A review. *International Journal of Hygiene and Environmental Health*, *214* (6), 449–460. https://doi.org/10.1016/j.ijheh.2011.05.001

Wilson, E. O. (1984). *Biophilia*. Cambridge, MA: Harvard University Press.

Woods Ballard, B., Wilson, S., Udale-Clarke, H., Illman, S., Scott, T., Ashley, R. & Kellagher, R. (2015). *The SuDS manual* (C753). London: CIRIA.

Woźniak, Ł. & Walczkiewicz, T. (2018). Mała retencja w Polsce w świetle rozwoju systemu ochrony przed powodzią. In *Współczesne problemy retencji wód*. Warszawa: Instytut Meteorologii i Gospodarki Wodnej – Państwowy Instytut Badawczy.

Wu, C-C., O'Keefe, J. M., Ding, Y. & Sullivan, W. C. (2024). Biodiversity of urban green spaces and human health: A systematic review of recent research. *Frontiers in Ecology and Evolution*, *12*, 1467568. https://doi.org/10.3389/fevo.2024.1467568

Yang, L., Kim, S., Park, J. & Lee, H. (2025). Urban park restorative effects in an integrated model of positive emotion and leisure involvement moderation. *Scientific Reports*, *15*, 19451. https://doi.org/10.1038/s41598-025-19451-3

Zarząd Zieleni m.st. Warszawy (2022). *Warszawa w kwiatach – wyniki 39. edycji konkursu*. Retrieved from: https://zzw.waw.pl/2022/08/30/warszawa-w-kwiatach-wyniki-39-edycji-konkursu/ [accessed: 25.09.2025].

Zhong, S-T. & Ren, J. (2024). Evaluation on nature-connected environment in building embedded landscape: Theory, detection, and case design. *Frontiers in Environmental Science*, *12*, 1453010. https://doi.org/10.3389/fenvs.2024.1453010

PROJEKTOWANIE DLA WODY I PIĘKNA. WPŁYW ROZWIĄZAŃ OPARTYCH NA NATURZE I ZRÓWNOWAŻONYCH SYSTEMÓW ODWODNIENIA MIEJSKIEGO NA ESTETYKĘ PROJEKTÓW ARCHITEKTONICZNYCH WYBRANYCH DZIELNIC WE FRANCJI I W POLSCE

STRESZCZENIE

Dążenie do zdrowszych i bardziej zrównoważonych miast wymaga wdrożenia rozwiązań opartych na naturze (NBS). W wielu przypadkach zrównoważone systemy odwodnienia miejskiego (SUDS) są wymagane przez obowiązujące przepisy prawne. Chociaż mogą one powodować pewne obciążenia finansowe w zakresie utrzymania, to poprawiają jakość projektów architektonicznych. Zbadanie możliwości wykorzystania SUDS w celu zwiększenia atrakcyjności estetycznej architektury oraz przegląd przykładów dobrych praktyk z dwóch wybranych dzielnic we Francji i w Polsce to główne cele pracy. Przedstawiono korzyści płynące z NBS w celu poprawy estetyki i zdrowia ludzi. Przeanalizowano ramy regulacyjne, a następnie omówiono korzyści, wyzwania i uwarunkowania związane z SUDS. W opracowaniu porównano możliwości wprowadzenia NBS w obu krajach. Przykłady wybranych osiedli pokazują, że zastosowanie NBS i SUDS jest możliwe i poprawia estetykę całych zespołów architektonicznych.

Słowa kluczowe: rozwiązanie oparte na naturze, NBS, zrównoważony system odwodnienia miejskiego, SUDS, estetyka, projektowanie architektoniczne, projektowanie urbanistyczne, Francja, Polska

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WOOD AS AN ARCHITECTURAL MEDIUM: AESTHETICS, FUNCTION AND SOCIAL PERCEPTION FROM A HISTORICAL AND CONTEMPORARY PERSPECTIVE

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ABSTRACT

The objective of this article is to present the role of wood in contemporary architecture from the perspective of aesthetics, technology and social perception. The study is based on a review of literature from 2020 to 2025 (Scopus, Web of Science) and an analysis of the authors' own projects. Wood's natural texture and colour are conducive to creating friendly spaces rooted in tradition, while modern technologies enable its use in large, energy-efficient buildings. In social terms, this strengthens the identity of a place and openness to interaction, combining heritage with innovation. The conclusions emphasise the importance of wood as a key material for sustainable design, integrating aesthetic, technical and social values.

Keywords: wood in architecture, aesthetics of materials, wood construction technology, social perception, sustainable architecture, original designs

INTRODUCTION

Architecture may be defined as a constant effort to organise physical and symbolic space in a manner that meets human needs, their ideas about the world, and their relationship with their surroundings. In this process, material is not merely a means to an end, but becomes the designer's partner, a participant in the narrative of space. Wood, a material with a deep historical presence in the field of construction, possesses the capacity to be shaped and to shape meanings and experiences. The contemporary return to wood in architecture is not a coincidence. This approach is indicative of a broader ambition to align design with the principles of sensuality, sustainability and human-centredness.

The utilisation of wood in the construction of edifices for residential, occupational, commercial and communal purposes has a long-standing historical precedent that spans multiple centuries. Its historical presence is both widespread and diverse, ranging from rural dwellings to monumental public buildings. In ancient cultures, wooden architecture was instrumental in shaping the rhythm of everyday and festive life, providing a framework for social and cultural practices. The practice of craftsmanship, the concept of local identity and the organisation of space are inscribed in wood, thus transcending the purely functional understanding of a building. In the contemporary context, there is a resurgence of interest in these qualities,

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which is inextricably linked to the imperative to redefine the relationship between architecture and its context, as well as the symbiotic relationship between technology and cultural memory.

It is nevertheless important to acknowledge that wood is not the same material it was in the past. The advent of contemporary technologies has resulted in its transformation into an engineering material with the capacity to compete with concrete and steel in terms of both strength and scalability. The utilisation of innovative wood-based products facilitates the construction of large-scale, energy-efficient buildings that adhere to the principles of sustainable construction (Rilatupa, 2021; Kuzman & Sandberg, 2023). The contemporary utilisation of wood transcends nostalgia, becoming an articulation of modern architectural thought that responds to climate and social challenges.

Technological change has been accompanied by a transformation in the aesthetic impact of wood. In contemporary spaces characterised by glass, concrete and aluminium, wood is experiencing a renaissance as a material with a distinct visual and haptic character. The warmth of its colour, the diversity of its textures and its natural irregularity are conducive to evoking deeply sensual reactions. Research on the perception of materials indicates that wood evokes a sense of comfort, closeness and calm, especially in work and everyday environments (Dai, Li & Zhang, 2023; Zhu, Wang & Zhao, 2023). Nevertheless, the aesthetic qualities of wood are subject to cultural interpretations and historical changes and are influenced by the social context and the individual experiences of its users.

The material also exhibits a social dimension, which assumes particular significance during periods of search for connections and identity in urban spaces. As a natural material, it is subject to the effects of ageing and wear and tear, which results in the accumulation of traces of use. This process of deterioration and the subsequent patina that forms make the material a carrier of time and history. In the fields of adaptive and conservation architecture, as well as in projects grounded in local narratives, it functions as a conduit between the present and the past, thereby fostering a sense of continuity and belonging (Khimesara & Shah, 2024). Spaces constructed from wood are frequently perceived as more ‘familiar’, less anonymous, and conducive to a sense of closeness and shared experience of a particular locale.

In recent years, there has been a marked increase in interest in wooden structures in Poland and worldwide. The utilisation of cross- and glued-laminated timber (CLT, GLT) technologies facilitates the construction of multi-storey and multi-purpose buildings, thereby reducing the carbon footprint and ensuring high performance (Kuzman & Sandberg, 2023). The substantial increase in the number of new wooden buildings in Poland by over 50% between 2018 and 2022 serves to underscore the significance of this material in sustainable construction strategies (Rilatupa, 2021). The evolution of prefabrication and digital processing technologies has led to a significant expansion in the formal and aesthetic possibilities of wood as a medium in contemporary architecture, positioning it as one of the most dynamic materials in current design.

The findings outlined above necessitate an analysis of wood from three distinct perspectives, which will be expanded upon in this paper: aesthetic impact, function and technology, and social perception. The objective of this article is to demonstrate the evolution of the perception of wood as an architectural material, from its traditional application in construction to contemporary projects that integrate technological innovation with the imperative to create sustainable and meaningful spaces.

METHODOLOGY AND MATERIALS

The present study constitutes a problem-oriented review, the objective of which is to present the role of wood in contemporary architecture from an aesthetic, technological and social perspective. The analysis was conducted from the perspective of an architectural theorist and practitioner, which allows for the combination of reflections derived from scientific literature with design experience.

The material basis consists of two groups of sources. The initial group consists of scientific publications from 2020 to 2025, indexed in the Scopus and Web of Science databases, focusing on wooden architecture, novel technologies in wooden construction, the aesthetics of the material, and its social reception. The second category comprises observations and conclusions derived from design practice, encompassing both the authors' personal projects and the analysis of objects created within a broader national and international context. The authors' own projects were selected based on their functional diversity, application of engineered wood technologies, and representativeness for the Polish architectural context. This combination makes it possible to capture both the empirical and technological dimensions, as well as the design reflection resulting from the authors' professional experience. The central research problem concerns how contemporary architectural uses of wood integrate the aesthetic, technological, and social dimensions in sustainable design. This, in turn, enables a more comprehensive view of the analysed problem.

The review is thematic in nature. The individual issues have been grouped around three axes that are considered key to contemporary reflection on wood in architecture. The first of these aspects pertains to the aesthetic qualities and methodologies employed in shaping the visual and haptic perception of wood, along with its relationship to tradition. The second part of the paper is dedicated to examining the function and technology, with a particular focus on the evolution of the structural utilisation of materials in the context of advancements in engineering, prefabrication, and sustainable construction principles. The third aspect pertains to the social perception of wood, encompassing its role in fostering a sense of place, comfort, and connection with the environment.

The selection of materials was deliberate. It was considered good practice to give priority to publications that combined technical, aesthetic and cultural perspectives, as well as studies that took the Polish context into account in a broader international context. The analysis was based on a comparison of research findings with practical observations of the design process, which allows us to capture the complexity of the relationship between theory and practice.

CONTEMPORARY DIMENSIONS OF WOOD IN ARCHITECTURE

The contemporary use of wood in architecture can be considered a multidimensional phenomenon, in which aesthetics, technology, function and social perception intertwine. In recent years, this material has undergone a significant evolution, transitioning from a material deeply rooted in the tradition of craftsmanship to a highly processed engineering material used in projects of various scales and degrees of complexity. This transformation has been accompanied by a change in its role in the cultural landscape and in the awareness of users.

The analysis presented in this chapter is approached via three distinct perspectives. The initial issue pertains to the aesthetic impact of wood; that is to say, the manner in which its presence within a given space influences the visual and haptic perception, and the extent to which these properties can be manipulated during the design process. The second part of the paper addresses issues of function and technology, with a focus on the possibilities offered by new wood-based products, prefabrication, and materials engineering. The third perspective pertains to the social perception of wood, encompassing the manner in which users and communities interpret its significance, ascribe symbolic values to it, and associate it with a sense of place identity.

This approach enables us to consider wood not only as a building material but also as an architectural medium that contributes to the creation of meanings and experiences of space. The ensuing subsections are devoted to an examination of these three aspects, which collectively constitute the contemporary image of wood in 21st-century architecture.

Aesthetic effect of wood

The aesthetic impact of wood encompasses both visual and tactile sensations; its presence in architectural spaces has been shown to evoke feelings of warmth, tranquillity and a connection with nature. In the context of contemporary architecture, wood is notable for its ability to engender a more sensual and intimate atmosphere, thereby counterbalancing the use of cold, impersonal materials.

Empirical studies have confirmed that wood significantly influences the perception of comfort. In an experiment conducted within a climate chamber, participants assessed their thermal sensation after entering a room with wooden walls, compared to a room with uniform plaster walls. The findings indicated that wood facilitated more rapidly attaining thermal neutrality in comparison to conventional materials, though the statistical significance was not invariably evident. Nonetheless, the visual effect exerted a discernible influence on the subjective perception of space (Gravelle, Stenson, Fretz & Van Den Wymelenberg, 2025).

A number of studies have been conducted that have explored the impact of combining wood with other materials. The study found that wood was perceived as the 'warmest' material, and its increased presence enhanced the feeling of warmth. On top of this, employing light colours and integrating diverse materials served to enhance the visual appeal of the furnishings. In contrast, combining wood with fabric resulted in diminishing its initial appeal (Kwak & Choi, 2025).

The subsequent analysis concentrated on the perception of untreated wooden façades, a characteristic of Scandinavian and German architecture. The findings indicated that preferences concerning the extent of wood ageing (e.g. the manifestation of grey colouration) exhibited variations in accordance with the nation and the personality traits of the respondents. Individuals who were introverted, conscientious, younger in age and possessed higher levels of education demonstrated a greater propensity to accept the raw, natural appearance of wood (Gustavsen et al., 2025).

This research has a direct impact on the design of both interiors and façades. The aesthetic impact of wood is contingent on its colour, texture, surface treatment and combination with other materials. This approach facilitates establishing a convivial and recognisable ambience, or a more pronounced sense of local heritage and convention.

Function and technology of wood

The contemporary use of wood in architecture is undergoing rapid development, driven by technological advances and increasing demand for sustainable construction methods. The utilisation of engineered wood solutions, such as CLT and dowelled cross-laminated timber (DCLT), facilitates the construction of multi-storey buildings that exhibit high performance and a low carbon footprint. It is becoming increasingly evident that they are becoming regarded as a viable alternative to concrete and steel in both residential and public utility projects.

There has been a clear rise in this segment in Poland. According to some studies, the number of new wooden buildings went up by about 52% between 2018 and 2022, and the value of the domestic wooden construction market in 2022 was around PLN 3.5 billion. This increase refers to new constructions compared with 2017 levels (Mazur & Winkler, 2025). Although still modest relative to Western European markets such as Sweden or Germany, it reflects growing national interest and institutional support for timber construction. However, the authors of this study emphasise that the pace of further development depends on the availability of raw materials and changes in legal regulations favourable to this type of investment (Mazur & Winkler, 2025).

From an international perspective, the growing role of CLT is particularly noteworthy. A review of the relevant literature suggests that this material has the potential to become one of the dominant construction materials in large-scale construction, especially in the context of carbon dioxide emission reduction (De Araujo & Christoforo, 2023). At the same time, technological development requires parallel improvements in fire

protection, including the use of protective coatings and encapsulation methods for components, which slow down the spread of fire (Hopkin et al., 2024).

Research into alternative construction solutions has shown that DCLT is characterised by high air tightness and favourable thermal properties, thus confirming its suitability for energy-efficient residential construction (Świrska-Perkowska, Wicher, Pochwała, Anweiler & Böhm, 2022).

In the context of climate policy, the importance of wood as a resource is also recognised. Projections indicate that augmenting CLT output to billions of cubic metres by the year 2100 could potentially lead to the permanent sequestration of billions of tonnes of carbon dioxide, both within forest ecosystems and within the structures themselves (Pitchford, 2025).

The evolution of prefabrication and modular technologies has led to a significant expansion in the formal and functional capabilities of wood. These solutions enable architects to construct structures with intricate geometries while maintaining a high degree of precision and reducing construction time. In this manner, engineered wood becomes a medium that combines rational structural requirements with aesthetic and environmental values.

Social perception of wood

The perception of wood in architecture is shaped by a complex network of cultural references, environmental factors and personal experiences of users. This material is firmly embedded within the collective memory of the nation. In Poland and numerous other countries, it is associated with both traditional architecture and new explorations of forms that are more conducive to human and environmental well-being. Consequently, the perception of wooden spaces is imbued with symbolic meanings that have the capacity to strengthen a sense of identity and belonging.

A plethora of studies on material perception have indicated that wood evokes positive emotional responses in users, which are associated with feelings of warmth, closeness and naturalness. In professional settings, the incorporation of wood has been demonstrated to enhance the perception of comfort and reduce stress levels among employees (Zhu et al., 2023). This effect is multisensory in nature; therefore, factors such as visual qualities are of significance, but also the texture, smell and acoustics of the material.

However, the social perception of wood varies and is subject to cultural context. Comparative studies on the perception of natural, untreated wood façades have demonstrated that the degree of acceptance of natural ageing processes varies between countries and demographic groups. As demonstrated in Figure 1, younger people who have received a higher level of education, who are more introverted and conscientious, were more likely to approve of the raw appearance of aged wood (Gustavsen et al., 2025). These findings, while indicative, are based on a limited sample and should therefore be interpreted cautiously. The findings of this study imply that individual differences in personality traits may serve as a contributing factor in the manifestation of preferences for natural materials.

Wood can also serve a socially integrating function. In public space designs, such as pavilions, squares and cultural facilities, this material helps to build a sense of community and ‘familiarity’ with a place. Perceived as less formal than concrete or glass, wooden elements of urban infrastructure facilitate spontaneous interactions between users and encourage them to spend more time in the space (Starzyk, Cortiços, Duarte & Łacek, 2024).

The social significance of wood is also pertinent to the relationship between architecture and local identity. In the context of architectural adaptations that preserve historical functions or perpetuate regional building traditions, wood assumes the role of a medium for conveying the narrative of a locale’s continuity. It can then act as a conduit between the past and the present, facilitating the establishment of social bonds and the protection of cultural heritage (Khimesara & Shah, 2024).

It is evident that the social perception of wood is not confined to mere aesthetic preferences. This phenomenon is the result of a combination of individual experiences, symbolic meanings and the real properties of the material. It is important to consider these factors during the design process in order to create spaces that are both functional and durable, and which are also deeply rooted in human experience.

DISCUSSION OF RESULTS

The collected analyses demonstrate that the role of wood in contemporary architecture extends beyond its structural value. The material under discussion occupies a space between emotion, technology and social narrative, thus facilitating a multifaceted understanding of its design potential.

A plethora of studies have demonstrated that the presence of wood has a significant impact on the creation of a sense of warmth and comfort within a given environment. This phenomenon has been found to enhance both visual and tactile sensations, thereby contributing to an overall positive and pleasant experience. Questionnaire and physiological analyses have been used to confirm this trend, with an increase in the proportion of wood in the material composition correlating with a higher rating of the friendliness and attractiveness of a space (Kwak & Choi, 2025). Empirical tests of aesthetic preferences, including those for wood joint details, indicate that forms with gentle shapes (e.g. curved segments) are most appreciated, which may have practical implications for the design of architectural details (Kuys & Mridha, 2024). The outcomes of this study call into question the limits of 'aesthetic functionality' and the extent of compromises that can be made between visual expression, economy and durability. This issue provides a foundation for future research, which will facilitate more precise differentiation of design decisions.

The substantial expansion of the timber construction market in Poland is indicative of a combination of factors, including an increase in market confidence in the material, as well as changes in regulatory frameworks and the emergence of advanced technologies (e.g. CLT, DCLT). The observed dynamic growth in the number of new timber structures indicates a real change in the construction paradigm (Ilgın, Karjalainen & Pelsmakers, 2023). Concurrently, associated technologies (e.g. fire protection, prefabrication, modularity, hybridisation) generate novel prospects in one respect whilst simultaneously highlighting domains in which standards and protective measures require further enhancement (Menzemer, Vad Karsten, Gwynne, Dragsted & Ronchi, 2025; Starzyk, Cortiços, Duarte & Łacek, 2025). It is imperative to undertake rigorous research to enhance our comprehension of the regulatory, technical and educational impediments that persist in curtailing the comprehensive utilisation of wood in large-scale buildings.

The public perception of wood is subject to fluctuation between a sentiment for tradition and aspirations for modern, sustainable construction. Research on aesthetic preferences indicates that acceptance of natural forms of wood depends, among other things, on the demographic and personality characteristics of the respondents (Kuys & Mridha, 2024; Menzemer et al., 2025). In an urban context, the use of wood has been demonstrated to contribute to the development of a narrative of place, fostering an environment that is perceived as comfortable and 'familiar', as well as facilitating stronger relationships with local heritage (Bo & Abdul Rani, 2025; Mair-Bauernfeind, Boiger, Asada & Stern, 2025). This finding lends further credence to the notion that designs incorporating wood can effectively cultivate a sense of belonging, a concept that aligns with broader discourses on place identity and placemaking.

FROM THEORY TO PRACTICE – SELECTED ORIGINAL CONCEPTS

In order to provide a practical illustration of the theoretical analysis presented, a selection of original projects and conceptual designs are presented below. These projects and designs incorporate wood in a significant aesthetic, technological and social role. Each example provided illuminates the issues that were discussed

earlier, demonstrating the feasibility of implementing the assumptions of the article in design practice. These projects represent a progression of the findings presented and the conclusions of the preceding discussion, demonstrating their practical application in design.

The construction of a residential and commercial building incorporating a daycare centre is hereby proposed. The concept (Fig. 1) integrates residential and care functions, with wood employed as a façade material in a vertical board arrangement with a light colour. The aesthetic of the building is inspired by its natural surroundings, creating a visual contrast with the modern form of the structure. The social function of the building necessitated the creation of amicable and accessible spaces, which was accomplished through the utilisation of materials that are perceived as warm and the incorporation of ecological solutions, such as a green roof and photovoltaic panels.

The concept of an energy-efficient kindergarten in Michałowice (Fig. 1b) serves as a paradigm of educational architecture, wherein the utilisation of wood plays a pivotal role in fostering an atmosphere of safety and openness. The functional layout and spatial solutions encourage children to interact with nature, thanks to large glazed areas and green roofs. The wooden slatted façade is distinguished by its light rhythm, which serves to accentuate the structure's perceived lightness and simultaneously integrates the building harmoniously into the surrounding landscape. The design also incorporates high energy efficiency standards, integrating both aesthetic and technological elements.

The construction of a service building with a boathouse in the Czerniakowski Port is illustrated in Figure 1c. The purpose of the building is twofold: it is intended for both port and recreational functions. The dark, vertical wooden cladding bestows upon the structure a distinctive, modern character, whilst simultaneously alluding to the traditional aesthetics of waterfront buildings. The integration of terraces and greenery on the roofs of these buildings serves two primary purposes. Firstly, it enables the structures to blend in with their surroundings, thus reducing the visual impact. Secondly, it provides additional functionalities, such as enhanced thermal comfort and aesthetic appeal. The ground floor's transparency fosters visual openness to the port space, thereby strengthening social relations between users and the locale.



Fig. 1. Case studies: a – residential and service building with a daycare centre for children with intellectual disabilities (2021), b – energy-efficient kindergarten in Michałowice (2020), c – multifunctional service building with bosun's office in Czerniakowski Port, Warsaw (2022)

Source: © Agnieszka Starzyk, Janusz Marchwiński and Mikołaj Donderewicz.

The concepts presented herein are illustrative and demonstrate the manner in which theoretical assumptions concerning aesthetics, technology, and the social perception of wood can be directly translated into design decisions. It is demonstrated that the conscious use of this material enables the creation of objects in which form, function and social meaning remain in consistent dialogue. This approach demonstrates that wood, when considered in the three dimensions discussed in the article, functions not only as a building material but also as a tool for shaping spaces rooted in culture, the environment and human experience.

CONCLUSION

The utilisation of wood in contemporary architecture is a material that exhibits a distinctive capacity to amalgamate aesthetic, technological and social values. This material has the capacity to influence the atmosphere of a given space, to respond to the needs of its users, and to serve as a tool for the construction of narratives that are rooted in the local context. Its incorporation into a design can imbue an environment with a more human, sensual dimension, thereby facilitating interaction with its surroundings.

From an aesthetic perspective, wood possesses a distinctive character that is derived from its inherent texture and colour variations, and its vulnerability to the effects of time. In the domain of technology, it demonstrates its capacity for the construction of contemporary buildings that require elevated structural and environmental standards. Within the social sphere, it has been demonstrated that this phenomenon fosters bonds with a place, strengthens identity and creates spaces that encourage interaction.

A thorough examination of the three dimensions of contemporary wood use reveals that it is not merely a structural element, but a fully fledged architectural medium. It has the capacity to combine tradition with innovation and to respond to both functional and cultural challenges. Its role in contemporary design appears to be of particular importance in the context of efforts to create sustainable architecture that is rooted in real human experience. This study is limited to architectural and perceptual dimensions of wood and does not encompass quantitative life-cycle assessment or comparative analysis with other sustainable materials such as bamboo or mycelium-based composites. These aspects will be addressed in future research.

It is evident that wood remains a material that necessitates a deliberate design approach; one that fully exploits its technical, aesthetic and social properties. In the future, it is likely to become one of the key elements in shaping spaces that are durable, meaningful and open to dialogue with people and the environment.

For practitioners, the findings highlight the importance of integrating aesthetic and social considerations into technical design decisions. Awareness of users' perceptual and emotional responses to wood can enhance both comfort and sustainability outcomes.

Authors' contributions

Conceptualisation: A.S., J.M. and V.M.; methodology: A.S.; validation: A.S., J.M. and V.M.; formal analysis: A.S., J.M. and V.M.; writing – original draft preparation: A.S., J.M. and V.M.; writing – review and editing: A.S., J.M. and V.M.; supervision: A.S.; project administration: A.S.

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REFERENCES

Bo, L. & Abdul Rani, M. F. (2025). The Value of Current Sense of Place in Architectural Heritage Studies: A Systematic Review. *Buildings*, *15* (6), 903. https://doi.org/10.3390/buildings15060903

Dai, X., Li, M. & Zhang, Y. (2023). Effects of wood texture and color on aesthetic pleasure: two experimental studies. *International Journal of Evaluation and Research in Education*, *12* (1), 125–134. https://doi.org/10.11591/ijres.v12.i1.pp125-134

De Araujo, V. & Christoforo, A. (2023). The Global Cross-Laminated Timber (CLT) Industry: A Systematic Review and a Sectoral Survey of Its Main Developers. *Sustainability*, *15* (10), 7827. https://doi.org/10.3390/su15107827

Gravelle, D., Stenson, J., Fretz, M. & Van Den Wymelenberg, K. (2025). Impact of Wood on Perception of Transient and Steady-State Indoor Thermal Environments. *Buildings*, *15* (10), 1698. https://doi.org/10.3390/buildings15101698

Gustavsen, G. W., Niekerk, P. B. van, Niklewski, J., Brischke, C. & Alfredsen, G. (2025). Exploring consumer perception of uncoated wooden cladding: a study across three European countries. *European Journal of Wood and Wood Products*, *83* (79). https://doi.org/10.1007/s00107-025-02235-x

Hopkin, D., Węgrzyński, W., Gorska, C., Spearpoint, M., Bielawski, J., Krenn, H., Sleik, T. Blondeau, R. & Stapf, G. (2024). Full-Scale Fire Experiments on Cross-Laminated Timber Residential Enclosures Featuring Different Lining Protection Configurations. *Fire Technology*, *60*, 3771–3803. https://doi.org/10.1007/s10694-024-01581-1

Ilgın, H. E., Karjalainen, M. & Pelsmakers, S. (2023). Contemporary tall residential timber buildings: what are the main architectural and structural design considerations? *International Journal of Building Pathology and Adaptation*, *41* (6), 26–46. https://doi.org/10.1108/IJBPA-10-2021-0142

Khimesara, S. & Shah, A. (2024). A Critical Enquiry of Material Ageing in Interior Architecture. *International Conference on Civil Engineering, Architecture and Urban Planning*, *IN0317*. https://doi.org/10.38027/iccaua2024in0317

Kwak, S. & Choi, K. (2025). Visual perceptions of wood-integrated material combinations: effects on psychological and physiological responses. *Journal of Wood Science*, *71* (20). https://doi.org/10.1186/s10086-025-02191-3

Kuys, B. & Mridha, M. (2024). Aesthetic Preference of Timber Joints in Architectural Products. *Sustainability*, *16* (1), 154. https://doi.org/10.3390/su16010154

Kuzman, M. K. & Sandberg, D. (2023). Engineered wood products in contemporary architectural use – a concise overview. *Wood Material Science & Engineering*, *18* (6), 2112–2115. https://doi.org/10.1080/17480272.2023.2264258

Mair-Bauernfeind, C., Boiger, T., Asada, R. & Stern, T. (2025). Social consequences of wood-based innovations: a generic analysis of sectoral differences in Austria. *International Journal of Life Cycle Assessment*, *30*, 1281–1305. https://doi.org/10.1007/s11367-024-02361-3

Mazur, Ł. K. & Winkler, J. (2025). Timber Construction in Poland: An Analysis of Its Contribution to Sustainable Development and Economic Growth. *Drewno. Prace Naukowe, Doniesienia, Komunikaty – Wood. Research Papers, Reports, Announcements*, *68* (215). https://doi.org/10.53502/wood-196236

Menzemer, L. W., Vad Karsten, M. M., Gwynne, S., Dragsted, A., & Ronchi, E. (2025). Public perception of fire safety and risk of timber buildings. *Wood Material Science & Engineering*, *20* (4), 755–768. https://doi.org/10.1080/17480272.2025.2459350

Pitchford, J. (2025, 25 July). B*uilding a high rise out of wood? Cross-laminated timber could make it possible*. NC State University News. Retrived from: https://news.ncsu.edu/2025/07/building-a-high-rise-out-of-wood-cross-laminated-timber-could-make-it-possible/ [access: 21.09.2025].

Rilatupa, J. (2021). Prospects of sustainable wood building architecture. *IOP Conference Series: Earth and Environmental Science*, *878*, 012017. https://doi.org/10.1088/1755-1315/878/1/012017

Starzyk, A., Cortiços, N. D., Duarte, C. C. & Łacek, P. (2024). Environmental and architectural aspects of wooden construction: a comparative analysis of selected issues of single-family housing in Poland and Portugal. *Acta Scientiarum Polonorum. Architectura*, *23*, 304–318. https://doi.org/10.22630/aspa.2024.23.23

Starzyk, A., Cortiços, N. D., Duarte, C. C. & Łacek, P. (2025). Timber Architecture for Sustainable Futures: A Critical Review of Design and Research Challenges in the Era of Environmental and Social Transition. *Buildings*, *15* (15), 2774. https://doi.org/10.3390/buildings15152774

Świrska-Perkowska, J., Wicher, A., Pochwała, S., Anweiler, S. & Böhm, M. (2022). Doweled cross Laminated Timber (DCLT) Building Air Tightness and Energy Efficiency Measurements: Case Study in Poland. *Energies*, *15* (23), 9029. https://doi.org/10.3390/en15239029

Zhu, Y., Wang, Q. & Zhao, F. (2023). Wood in office spaces: The impact of different wooden furniture on aesthetic evaluation. *Frontiers in Psychology*, *13*, 986627. https://doi.org/10.3389/fpsyg.2022.986627

Starzyk, A., Marchwiński, J., Milošević, V. (2025). Wood as an architectural medium: aesthetics, function and social perception from a historical and contemporary perspective. *Acta Sci. Pol. Architectura*, *24*, 380–389, DOI: 10.22630/ASPA.2025.24.26

DREWNO JAKO MEDIUM ARCHITEKTURY: ESTETYKA, FUNKCJA I PERCEPCJA SPOŁECZNA W UJĘCIACH HISTORYCZNYM I WSPÓŁCZESNYM

STRESZCZENIE

Celem artykułu jest ukazanie roli drewna we współczesnej architekturze z perspektywy estetyki, technologii i odbioru społecznego. Opracowanie opiera się na przeglądzie literatury z lat 2020–2025 (Scopus, Web of Science) oraz analizie realizacji autorskich. Drewno, dzięki naturalnej fakturze i barwie, sprzyja tworzeniu przestrzeni przyjaznych i zakorzenionych w tradycji, a nowoczesne technologie umożliwiają jego zastosowanie w dużych, energooszczędnych obiektach. W wymiarze społecznym zastosowanie drewna jako budulca wzmacnia tożsamość miejsca i otwartość na interakcję, do tego łączy dziedzictwo z innowacją. Wnioski z przeprowadzonej analizy podkreślają znaczenie drewna jako materiału kluczowego dla projektowania zrównoważonego, integrującego wartości estetyczne, techniczne i społeczne.

Słowa kluczowe: drewno w architekturze, estetyka materiałów, technologia budownictwa drewnianego, percepcja społeczna, architektura zrównoważona, projekty autorskie

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COMPARATIVE ANALYSIS OF BUILDING PERMITS ISSUED IN POLAND AND SELECTED EUROPEAN COUNTRIES BETWEEN 2019 AND 2024 IN THE CONTEXT OF ECONOMIC CONDITIONS

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ABSTRACT

The article aims to compare the number of building permits issued in Poland and four European countries between 2019 and 2024, with country selection based on GDP per capita in the reference year 2019. The hypothesis assumes that global crises, such as the COVID-19 pandemic and the war in Ukraine, significantly affected investment activity in the construction sector, particularly in less developed economies. The analysis showed that in Poland's central region, the number of building permits decreased from 49,632 in 2019 to 42,271 in 2024. In lower-GDP countries, such as Croatia and Romania (13,898.49 and 11,601.89 EUR per capita in 2019, respectively), greater fluctuations in construction activity were observed, while Romania recorded an increase in non-residential permits, reaching 4,033,925 in 2023. The resilience of the construction sector to economic crises has been empirically confirmed, and research has shown the need to standardise data reporting across EU countries.

Keywords: building permits, global crisis, gross domestic product, GDP, country's economy, construction site, construction cycle

INTRODUCTION

The impact of COVID-19 on the economy

At the end of 2019, a new, highly contagious and dangerous virus from the *Coronaviridae* family began appearing in Wuhan, China (Rothan & Byrareddy, 2020). This virus was named "Coronavirus disease 2019" or COVID-19. It caused significant mortality among vulnerable groups and spread quickly from person to person around the world. Within a few months, it became a major health crisis, and the World Health Organization (WHO) officially declared it a pandemic in March 2020 (World Health Organization. Regional Office for the Eastern Mediterranean [WHO EMRO], 2020). All countries that detected COVID-19 cases put strict health measures in place to stop the virus from spreading, such as widespread testing, tracking who got sick, and limiting people's movements. However, these steps were not enough to stop the infection, so governments had to enforce stay-at-home orders (Sumalla-Cano et al., 2022).

The COVID-19 pandemic has profoundly disrupted the global economy, affecting almost every area of business, society, and economic activity. One of the primary challenges faced by the construction sector was

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supply chain disruptions. Lockdowns and restrictions led to delays in the delivery of materials and equipment, affecting project timelines and increasing costs. Quarantine measures and workforce shortages reduced companies' production capacity, leading to delays and shortages in supply. These difficulties were then amplified by disruptions in transportation and logistics, making it impossible to ensure timely delivery to construction sites. As a result, construction companies faced significant project delays and rising costs. This chain of effects forced many firms into financial distress, which ultimately led to layoffs and reductions in employment. Consequently, the construction sector suffered substantial losses, negatively impacting national economies (Ogunnusi et al., 2020; Biswas et al., 2021; Sumalla-Cano et al., 2022). Looking ahead, the construction sector in Europe faces the task of addressing the long-term impacts of the pandemic. This includes adapting to new health and safety standards, overcoming supply chain vulnerabilities, and ensuring a steady workforce. The lessons learned during this period will be crucial in building a more resilient and sustainable construction sector in the future.

The pandemic and the construction sector in Poland

As in the rest of Europe, Poland faced challenges in the housing market, aggravated by the pandemic and subsequent shocks. The pandemic caused significant changes in cities, negatively affecting areas such as jobs, home sales, new investments, and growing businesses. To stop the virus, governments put many restrictions in place that affected how businesses and people socialised. Many people lost their jobs, which led to a decline in home sales and to more people taking out loans and using credit (Czech, Karpio, Wielechowski & Woźniakowski, 2020; Kaźmierczak, 2021; Łaszek, Olszewski & Augustyniak, 2024; Wieczorek & Dzięcioł, 2025). The COVID-19 pandemic had a significant impact on Poland's credit market for both households and businesses. In the early phase, banks tightened lending policies, especially for businesses, marking the largest restriction since 2009. By 2021, banks eased household credit conditions, particularly for mortgages and consumer loans (Narodowy Bank Polski [NBP], 2021). Government support programmes, including interest subsidies for affected businesses, helped improve liquidity. Despite these measures, the pandemic affected banks' credit portfolios, and the risk of non-performing loans remains a major concern for the financial system (Lusztyna, 2022). Many construction sites faced delays or stopped completely due to an insufficient workforce and materials not arriving on time. This was largely due to COVID-19 restrictions, which limited the number of workers on site and disrupted supply chains.

Additionally, rising material costs and logistical challenges further slowed construction projects. The uncertainty in the labour market and delays in permits also contributed to postponed investments, affecting both residential and commercial projects. As a result, overall construction activity in Poland declined temporarily, but gradually began to recover as restrictions eased and supply chains stabilised (Dutka, Stołecka & Janiak, 2021; Wieczorek & Dzięcioł, 2025).

European Union responses to the economic crisis

In Poland, support programmes for small and large businesses have been implemented, interest rates on loans have been reduced, and even subsidies for loan instalments have been introduced for businesses affected by the pandemic. Similar programmes have been implemented in other European countries. Many countries launched various financial support programmes to mitigate the economic consequences. These monetary measures have been directed at various areas, such as aid for small and medium-sized enterprises (SMEs), direct expenditure related to the fight against the pandemic, benefits for the unemployed, and household payments. The widespread support was intended to help businesses and families, but it often contributed to inflation, short-run stabilisation, and inflationary pressures (Brenninkmeijer, 2020; Fernández, 2020; Pappa, Ramos & Vella, 2024). During the pandemic, countries' support programmes were in place for every enterprise. Their primary purpose was to support business activity and improve the mood of entrepreneurs. Similar dynamics were observed across the EU, especially in the construction sector, which suffered serious disruptions. The financial measures were aimed at stabilising supply chains and their logistics.

Another cause of the global crisis was the energy crisis that began in 2020, when the pandemic brought economies to a halt and energy demand fell, limiting the extraction of raw materials. When economies began to thaw in 2021, demand rebounded faster than supply, causing gas, coal, and oil prices to spike. Europe, heavily dependent on Russian gas, began to experience shortages, and Russia further restricted supplies. After the outbreak of war in Ukraine in 2022, the situation escalated, with gas and energy prices reaching record levels. In Poland, the costs of heating, fuel, and electricity rose sharply, increasing inflation and the burden on households. At the same time, housing construction costs exploded as the production of cement, steel, and the transport of materials became more expensive. Developers had to put some projects on hold, and individual investors felt the pressure of rising bills. The government introduced energy shields and subsidies to mitigate the effects of the crisis. Across Europe, countries took similar protective measures and began to invest heavily in supply diversification, liquefied natural gas terminals, and renewable energy sources (Zhou et al., 2025). This crisis became one of the main factors that drove up the cost of living and construction in 2022–2023 and accelerated the energy transition on the continent.

Logistics and challenges in the European Union construction sector

Logistics is essential due to the numerous actors involved, frequent transportation needs, and the high variability in construction projects (Leifgen & Kujajewski, 2018; Rakhmatullina, Sosunova & Zubtsova, 2022; Fredriksson, Kjellsdotter Ivert & Naz, 2025). Effective logistics can create value through trust and commitment among actors, although challenges such as delayed actor involvement and lack of coordination can arise (Fredriksson et al., 2025). Effective logistics planning requires coordination among all stakeholders, including logistics planners, site managers, and contractors (Said & El-Rayes, 2014; Leifgen & Kujajewski, 2018). The construction sector faces challenges due to varying demand, which impacts logistics performance related to inventory and transportation costs (Vidalakis, Tookey & Sommerville, 2011). Inefficiencies in the construction supply chain are exacerbated by intricate logistics systems, isolated planning across different segments, and fragmented transport functions, leading to macro-level visibility issues and adverse sustainability impacts (Dhawan, Tookey & Poshdar, 2024). The EU construction sector faced several logistical challenges from 2019 to 2024. These challenges are multifaceted and stem from various factors, including infrastructure constraints, waste management, skilled labour shortages, and the need for technological advancements. The increase in freight transport has put significant pressure on EU infrastructure, leading to congestion on roads, rail links, and harbours. This congestion hampers efficient logistics operations and necessitates improvements in transport networks. Establishing an efficient trans-European transport network (TEN-T) remains a high priority, with ongoing revisions to guidelines aimed at improving freight and logistics flows (Tymoshchuk, Suray, Hrebeniuk, Zadoia & Selishchev, 2025). Investments in infrastructure projects and international partnerships are crucial for optimising transport and logistics.

One of the key effects of the pandemic was the implementation of modern technologies in the construction sector. Digital technologies, namely building information modelling and advanced logistics solutions, are essential for transforming construction techniques and reducing costs (Kastiukas & Zhou, 2019; Vasiliev & Bruskin, 2022). However, the overwhelming number of technological solutions can discourage companies from implementing them effectively. Moreover, these innovations involve not only significant financial investments, but also human resource challenges, such as resistance to change, the need for organisational changes, or the need for employees to acquire new digital skills. Such technology is used in modern construction and contributes to faster information transfer between different branches. In addition, during the COVID-19 pandemic, construction inspectors used it to monitor progress and check the quality of implementation. This is a considerable development in the economic sector, which, in the event of future global crises, could facilitate work on many construction sites and reduce employee layoffs (Wieczorek & Dzięcioł, 2025).

Construction prices in the European Union

The construction sector in the EU has experienced significant fluctuations in material prices from 2019 to 2024, influenced by various economic, political, and global factors (Amca, Yorucu & Kırıkkaleli, 2025). The COVID-19 pandemic and the conflict between Ukraine and Russia caused building material prices to soar due to international tensions, supply difficulties, and the shortage of certain products, leading to the contraction of construction activity in the euro area (Hazam & Ouhna, 2024; Sjekavica Klepo, Damić, Milaković, Radaković & Peroš, 2025). Political, economic, and financial risks further increased costs, with empirical studies confirming their significant negative impact on the EU construction cost index (Amca et al., 2025). This has led to delays and even stoppages in construction projects, further driving up costs. Rising interest rates and inflation rates have also contributed to the rising costs of construction materials (Amca et al., 2025). These economic factors have made it more expensive to finance construction projects, adding to the overall cost burden.

Figure 1 presents values in percent for producer prices and costs in the EU. Based on Figure 1, between 2019 and 2024, an increase was recorded from 90 index points in 2019 to 125 index points in 2024, with 2021 at 100 index points. The largest increase was recorded in the years 2021–2023, where the difference was about 20 index points, from 100 index points in 2021 to 118 index points in 2023. However, in 2024, producer prices were about five index points higher than costs. This growth shows that despite the collapse of the global economy, the EU economy continued to grow slightly due to a number of factors.

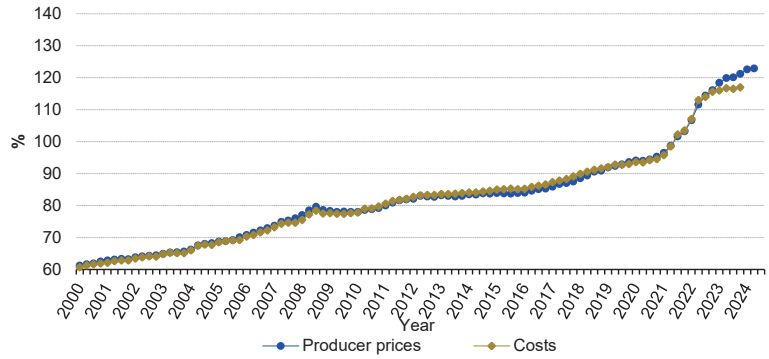


Fig. 1. Construction producer prices and costs in the European Union in 2000–2024, unadjusted quarterly data (2021 = 100)

Source: Eurostat (2025a).

Empirical evaluation of the impacts of political, economic, and financial risks on the cost of construction materials has shown that economic, political, and financial risk indices negatively affect the construction cost index across the EU (Amca et al., 2025). The impact of the global pandemic, supply chain disruptions, and international tensions has led to increases in material prices, affecting the resilience of companies operating in the construction sector (Hazam & Ouhna, 2024). It was found that the construction cost index in the EU area has shown continuous growth over the last two decades, particularly in the period following the COVID-19 pandemic. Stabilisation was evident in slow but steady growth from 2021 to 2024, reaching 117 index points in 2024. The main reason was stability policies, the implementation of new aid, recovery, and subsidy programmes for EU countries, and strong country economies, which, despite the problems caused by the crisis across the EU, did not experience significant declines in 2019–2024.

Gross domestic product dynamics in Europe

The global crisis had a significant impact on the EU, as it did on the rest of Europe. Construction prices in Europe were highly volatile between 2019 and 2024, mainly due to the COVID-19 pandemic and supply chain disruptions. Activity slowed in 2020 because of lockdowns and labour shortages, but demand rebounded in 2021 with resumed projects and stimulus measures. By 2024, price growth had moderated as supply chains recovered, though costs remained above pre-pandemic levels. The period highlights the sector's vulnerability to global shocks and the strong impact of external economic factors (Attinasi, Balatti, Mancini & Metelli, 2025).

Another indicator for determining the quality of a country's economy is gross domestic product (GDP). It is the total monetary value of all goods and services produced within a country's borders during a specific period and is a key indicator of economic performance. In the EU, GDP is used not only to assess overall economic output but also to monitor economic cohesion between member states. Although younger member states have generally experienced faster economic growth since the 2004 enlargement – driven by access to the single market, foreign investment, and EU funds – the convergence process remains uneven. While some regions have caught up quickly, others continue to lag behind due to structural and institutional challenges. As research shows, achieving sustainable and inclusive GDP growth across the EU requires deeper integration, targeted investment, and policies that address both productivity gaps and regional disparities (Mucha-Leszko & Twarowska, 2016; Pietrzykowski, 2019; Cieślik & Turgut, 2021). Contemporary economic development processes in European countries are characterised by significant diversity, which is particularly evident in the years 2019–2024 under the influence of two major crises: the COVID-19 pandemic and the war in Ukraine. GDP per capita remains one of the basic indicators used to compare the level of development of countries, and its volatility during crises allows us to identify the scale of the shock and the ability of a given country to rebuild its economy (Balakrishnan, Rabier, Ebeke, Firat & Malacrino, 2022; Licchetta & Mattozzi, 2023; Wieczorek & Dzięcioł, 2025).

Objective and scope of the analysis

The main objective of this analysis is to examine the dynamics of building permit issuance in selected EU countries between 2019 and 2024 and compare them with the situation in Poland. The analysis examines influencing factors, with a particular focus on trends and disruptions caused by external shocks such as the COVID-19 pandemic. The scope of the study covers selected European countries, allowing for cross-country comparisons and highlighting similarities and differences in the development of the construction sector (Petrova & Sznajder Lee, 2024). However, the main focus is on building permits as an indicator of construction activity. The analysis also considers the role of construction materials and supply chain challenges, which have indirectly affected the speed and scale of new construction projects (Mucha-Leszko & Twarowska, 2016; Cieślik & Turgut, 2021; Dai, Gao & Ma, 2024).

This article aims to analyse the dynamics of GDP per capita for selected countries in the years 2019–2024, taking into account the impact of global crises, such as the COVID-19 pandemic, as well as the context of European economic and environmental policies. The study also shows the correlations between GDP per capita for selected countries and the number of building permits issued in the years described. Data for all selected countries regarding GDP is presented in a uniform manner, where GDP is per capita and industry (including construction) is in percentages of GDP. The currency has been standardised and converted from the average annual exchange rates for each year from 2019 to 2024, from USD to EUR, based on data from the National Bank of Poland (NBP, 2019–2024). Data on building permits contain information for each of the 12 months of the year and are presented in an annual comparison for each country in relation to Poland. The analysis is set in the context of European economic, fiscal, and environmental policies, which

have significantly shaped the conditions for business and investment activity during the period under study. In addition to the macroeconomic perspective, the study focuses on the construction sector as one of the key areas of the economy. This area reflects the overall condition of the country's economy. To this end, the relationships between GDP per capita in selected countries and the number of building permits issued in 2019–2024 are presented. This approach allows for the identification of quantitative trends in construction development and changes in the level of prosperity of societies or the structure of the economy. The observation also concerns the dynamics of infrastructure and housing investments that affect the development of European countries. The analysis includes a comparison of two countries with a lower GDP than Poland and two countries with a higher GDP, which will allow for an assessment of the diversity of economic responses and the identification of factors supporting or limiting economic growth in different conditions. This comparison makes it possible to capture the diversity of economic responses and better understand the factors influencing economic development in different socio-economic conditions. The aim of this comparison is to show the extent to which the level of economic development, the availability of resources, and public policy influenced the issuance of building permits and investment activity in individual countries. The selected countries belong to Europe, but each of them has its own standards for presenting data and making it available. For this reason, for some countries, the data is not specific, but shows the general scale of building permits issued. This article – after analysing four European countries in comparison to Poland – answers questions such as: To what extent does the GDP per capita growth rate in individual EU countries translate into the number of building permits issued? Also, do countries with higher GDP per capita have a more resilient construction sector to economic crises, such as the COVID-19 pandemic, compared to countries with lower GDP per capita?

DATA AND METHODS

Selection of countries and time

According to the European Commission's forecast, the divergence from the pre-pandemic economic growth path is significantly greater than the corresponding divergence during the previous crisis. Analyses relating to the GDP of the EU-27 have been created, predicting a 7.4% decline in 2020, as well as that pre-crisis levels will not return immediately, with the result that many companies will go bankrupt and the number of employees will drop significantly (Brenninkmeijer, 2020).

Based on Eurostat data, the real GDP rate of change in 2019–2024 for the EU is taken into account. In 2019, the change was 2%, but it was observed that for EU countries, there was a decline in 2020 to a value of −5.6% compared with the previous year. This decline was caused by the COVID-19 pandemic. The world was paralysed, people were quarantined, and small and large businesses suspended or closed their operations. However, in 2021, there was a significant increase to 6% compared to the previous year. The following years saw a return to the higher values of before 2019 and an attempt at stabilisation. However, slight downward fluctuations in 2022 were caused by the war in Ukraine, which disrupted the supply chain of raw materials from Ukraine to EU countries. In 2024, the value was about 1.5%, which means that the economies of countries are recovering after the global crisis. The chart shows a comparison of GDP values for European countries in 2019 (Fig. 2).

The values presented in Figure 3 in euros have been converted using the weighted average exchange rate for 2019, where 1 USD = 0.893 EUR, based on historical data from the National Bank of Poland on 17 September 2025 (NBP, 2019–2024). In 2019, GDP per capita, a measure of economic activity, showed substantial differences across the chosen countries. The research methodology is based on the analysis of statistical data obtained from the World Bank for selected countries. The selection of countries for analysis was based on GDP per capita values in comparison to Poland.

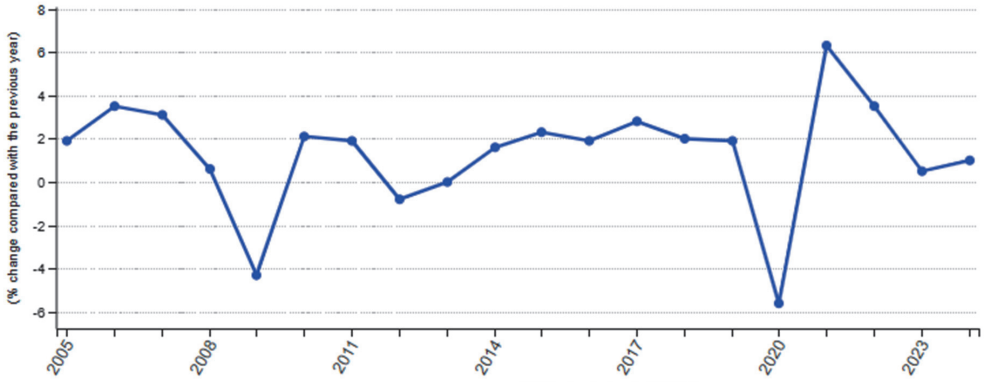


Fig. 2. Real gross domestic product rate of changes in the European Union in 2005–2024

Source: Eurostat (2025d).

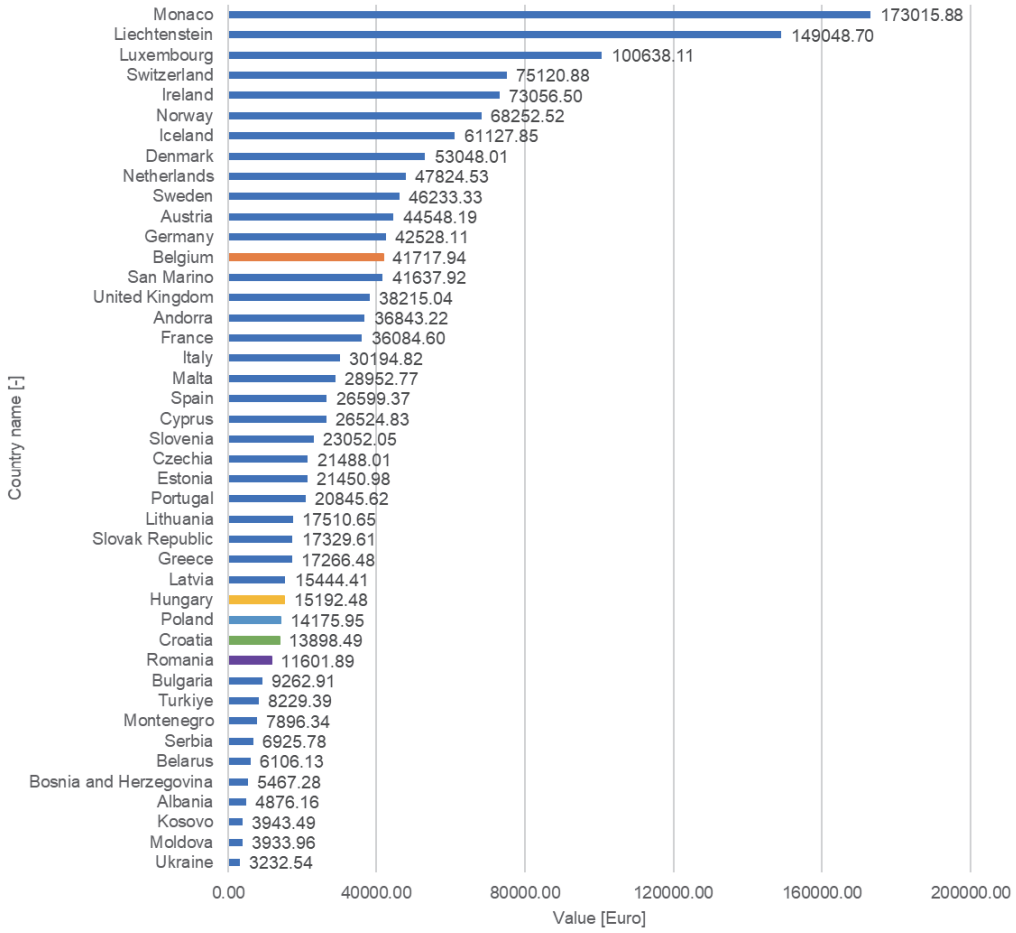


Fig. 3. Volume of gross domestic product per capita in 2019 for European countries

Source: own work based on World Bank [WB] (2025).

The GDP indicator for Poland, based on Figure 3, is 14,175.95 EUR. Two countries with a lower GDP than Poland were selected: Croatia at 13,898.49 EUR and Romania at 11,601.89 EUR. Furthermore, two more countries with a higher GDP than Poland were also selected for analysis: Belgium at 41,717.94 EUR and Hungary at 15,192.48 EUR. All countries have statistical data available from Eurostat or the World Bank, which facilitates comparison. Access to data for these countries was also free of charge and could be obtained from the central national statistical services' websites for individual countries. In addition, each of the selected countries is located in Europe, which makes it easier to compare them in terms of regulations and trade. Data such as GDP, inflation, and trade are also compared because the countries belong to similar economic regions in Europe. The selection of these countries allows us to show the differences and similarities in economic development, industrial structure, and standard of living, as well as how they cope with global conflicts. The analysis concerns the number of building permits issued in 2019–2024. These years were selected for comparison because they are the years before, during, and after the global pandemic crisis and the war in Ukraine, which created a lot of financial problems, logistics, and supply chain issues.

The comparison will be carried out using Excel in tabular form for individual countries against Poland. As part of the comparative analysis, data on GDP per capita for selected countries were collected. The comparison aims to determine Poland's position in relation to countries with higher and lower GDP levels. The reference year for the countries for analysis was 2019. This year was chosen because it was the year before global crises such as the coronavirus pandemic and the war in Ukraine. Moreover, the economies of these countries were stable, which allowed for a reliable assessment of the share of sectors such as construction in GDP per capita. Based on data from that year, the countries analysed were selected in relation to Poland's GDP value. The analysis also covered the percentage share of the industry sector in GDP. The comparison of economic factors will be presented in bar and line charts. Countries with a lower GDP will be listed on one chart together with Poland, and countries with a higher GDP than Poland will be listed on another chart together with Poland. This approach allows for a better understanding of differences in economic development and potential factors influencing the economy of a given country. The analysis also covered GDP per capita and industry (including construction) values for each country, as shown in the summary charts, together with a comparison to Poland. This data will be presented in charts. In addition, a comparison table will be created for Poland showing each type of building in 2019 and 2024, and the percentage changes. For each chart and table, an analysis was performed comparing the country to Poland and the number of permits issued in 2019–2024. The reference year is 2019.

Limitations

The collected data comes mainly from the websites of statistical offices of selected countries, as well as from Eurostat and national statistical offices for each chosen country: Poland – Statistics Poland (GUS), Croatia – Croatian Bureau of Statistics (DZS), Romania – National Institute of Statistics (INS), Hungary – Hungarian Central Statistical Office (KSH) and Belgium – Statistics Belgium (Statbel). Data aggregators such as Statista and the World Bank were also used.

Eurostat data is available free of charge, but there is a lack of completeness of data for the countries selected for analysis; therefore, statistical offices of selected countries were used. Eurostat divides types of construction into building and civil engineering works. Eurostat uses a data nomenclature in which a building is defined as a structure with a roof, built for permanent purposes and capable of being used by people. It does not need to have walls, but it must have a roof, and there must be a boundary that defines the individual character of the building intended for separate use. Buildings are divided into residential and non-residential buildings. A residential building is a building for which at least half is used for residential purposes. A non-residential building is a building that is used or intended mainly for non-residential purposes (Eurostat, 2025b). A civil engineering work is a construction not classified under buildings, for example, railways, roads, bridges, highways, airport runways, and dams (Eurostat, 2025c). In addition, data aggregators were used to combine all available and easily

accessible data for detailed analysis. Furthermore, despite applying the same rules to all selected European countries, statistical offices do not standardise data and have different ways of making data available. Poland presents the full data for each type of building for 2019 and 2024, and by the region of the country. The chart will present values for total building permits in selected years. For Croatia, the chart will show total building permits and residential buildings compared to Poland. According to Eurostat data, these types of buildings are community buildings. In Poland, transport infrastructure facilities will be shown on a chart, including roads, tram tracks, railway tracks, ports, waterways, and airports. In Romania, the national statistical services do not specify whether buildings are residential or non-residential. However, based on Eurostat data, non-residential buildings are defined as buildings that are mainly used or intended for non-residential purposes.

For Belgium, the only information obtained is the totals for residential buildings in the years 2019–2024. Finally, for Hungary, the data obtained for comparison are values for issued dwelling construction permits and construction in 2019–2024. The term 'dwelling construction' is the same as 'residential building' in Eurostat terminology. Croatia and Romania did not have data for 2019, which makes a full comparison difficult. Therefore, the comparison was made for the years 2020–2024.

National statistics services in each country differ in the way they present the quantity and descriptions of data. Often, these are general data compiled for specific years. However, such data has been analysed in a way that best reflects the potential and economic growth of individual countries. Based on the data obtained, our own figures were created and analysed based on data received for selected countries.

RESULTS AND DISCUSSION

The construction sector in Poland

The construction sector in Poland includes not only multi-family buildings and industrial facilities, but also roads, industrial and warehouse buildings, transport infrastructure facilities, and water structures. In Poland, an average of 105,000–110,000 building permits for residential buildings were issued annually between 2019 and 2024 (Główny Urząd Nadzoru Budowlanego [GUNB], 2025). The total number of building permits issued for all types of buildings is shown in Figure 4. The economy is mainly based on industry, construction, and raw materials, but this article shows the country's economic situation based on the number of building permits issued between 2019 and 2024.

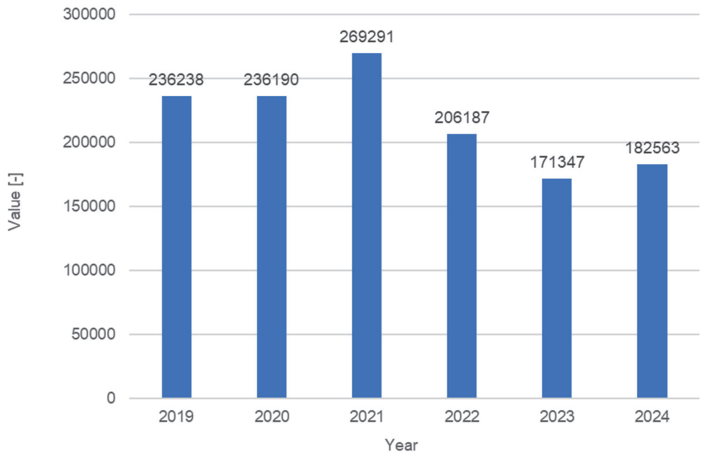


Fig. 4. Total building permits in Poland in 2019–2024

Source: own work based on GUNB (2025).

Between 2019 and 2024, Poland's economic situation was unstable, which had a direct impact on the construction sector. An analysis of the number of building permits issued during this period shows clear volatility, which can be linked to global and regional crisis events, such as the COVID-19 pandemic and the armed conflict in Ukraine that has been ongoing since 2022.

In 2019, amid macroeconomic stabilisation and a growing economy, 236,280 building permits were issued in Poland. This was a sign of a developing investment market and strong interest in the real estate sector. Despite the outbreak of the pandemic, 2020 did not bring a drastic decline. The construction sector showed great flexibility and adaptability to new realities, such as sanitary restrictions and changes in work organisation. The number of permits issued remained at a similar level to the previous year (Rachwał & Dominiak, 2022). The total number of permits in 2020 was 236,190. In 2021, there was a significant increase in construction activity, with 269,291 permits issued, which represented a 14% increase compared to 2019. This phenomenon can be explained by the accumulated investment demand after a period of pandemic-related decision-making suspensions, improved lending conditions, and active investment support policies on the part of the government and European institutions. Unfortunately, the positive trend did not last long (Kraska & Kot, 2024). The year 2022 brought a significant decline – the number of building permits decreased to 206,187, which represented a 12.7% decrease compared to 2019. The year 2023 proved to be the most difficult period for the Polish construction sector in the analysed time frame. Only 171,347 building permits were issued. Factors contributing to this situation include the ongoing war in Ukraine, a deepening labour shortage, limited availability of materials, and high inflation. The increase in investment financing costs and economic uncertainty discouraged many investors from starting new projects. In 2024, the first signs of stabilisation and recovery in the construction sector appeared. The number of permits issued increased to 182,563, an increase of 6.6% over the previous year and a decrease of 22.7% from 2019. The main factors shaping demand for housing in 2023–2024 were financial conditions in the country, such as high interest rates in 2022, subsequent cuts and easing of credit criteria, and government programmes for mortgagors.

The key factors were rising prices of construction materials, difficulties with their transport, and the outflow of workers from Ukraine. As a result of the war, many Ukrainian workers employed on construction sites returned to their country to take part in their country's defence. Developers and individual investors faced record construction costs, which halted some projects and limited the future supply of housing (Sochacki, 2024; Wieczorek & Dzięcioł, 2025).

Based on Figure 4, which shows the situation in the construction sector in 2019–2024 in terms of building permits issued for Poland, Table 1 shows the breakdown by specific types of buildings. For the period 2019

Table 1. Number of building permits issued for specific types of buildings in Poland in 2019–2024

Year	TB	CA	SB	MB	RB	PB	FB	IWB	TF	WS	PP	OF
2019	236 238	949	113 641	10 903	1 931	10 595	14 028	6 184	3 872	422	28 325	46 787
2020	236 190	1 037	121 366	11 557	1 878	9 699	12 208	5 626	3 739	493	22 825	46 802
2021	269 291	1 961	150 087	17 661	2 692	10 752	12 853	6 673	3 750	288	19 666	44 869
2022	206 187	908	113 803	15 619	2 590	10 631	10 508	6 003	3 436	329	15 331	27 937
2023	171 347	1 049	88 259	13 289	2 748	9 449	10 094	5 885	3 379	359	12 184	25 701
2024	182 563	582	99 282	16 247	2 022	9 851	9 696	5 346	3 383	302	9 052	27 382

TB – total number of buildings, CA – including those in closed areas, SB – single-family buildings, MB – multi-family buildings, RB – collective residential buildings, hotels, and accommodation buildings, PB – public utility buildings, FB – farm buildings and livestock buildings, IWB – industrial and warehouse buildings, TF – transport infrastructure facilities, WS – water structures, PP – pipelines, telecommunications and power lines, OF – other facilities.

Source: own work based on GUNB (2025).

to 2024, the lowest number of total buildings (TB) was in 2023. However, between 2019 and 2021, the number of building permits issued showed an upward trend for TB, including those in closed areas. An increase was recorded until 2021. From 2021, there was a marked decline, which reached its lowest point in 2023 for TB. This decline was a consequence of external macroeconomic factors: the COVID-19 pandemic, the war in Ukraine, the monetary policy, and improved credit conditions. These factors contributed to a reduction in the availability of workers, an increase in the prices of building materials and a weakening of investment. In 2024, a slow growth was expected, which means the reconstruction of the country's economy, an increase in the importance of construction, and an increase in the number of building permits issued.

Single-family buildings, multi-family buildings, collective residential buildings, hotels, and accommodation buildings showed positive growth in 2019–2021, followed by a decline until 2023, with a rebound for SB and MB in 2024. Multi-family buildings stood out in 2024, with their number increasing by 49% compared to 2019, which can be linked to the growing demand for multi-family housing in cities. No trend was observed in types such as public utility buildings, farm buildings and livestock buildings, industrial and warehouse buildings, transport infrastructure facilities, and water structures. However, most non-residential segments are expected to see a decline in 2019–2024: PB by 7%, FB by 31%, and IWB by 14%, with a temporary peak in 2021. This is not a regular occurrence due to the temporary nature of investments. Investments in water structures, which include dams, weirs, and retention reservoirs, or transport infrastructure facilities, depend on public funds and have long implementation cycles. Due to the long-term nature of use and the lack of urgent hydrotechnical needs, the number of permits in this category remains low. The highest number was in 2020 for 493 WS permits. In the area of transmission networks, pipelines, telecommunications, and power lines, there is a clear downward trend, from 28,325 permits in 2019 to 9,052 in 2024 - a difference of 68%. This may be the result of the completion of earlier infrastructure projects and financial and regulatory constraints. A similar downward trend has been observed for other facilities, from 46,787 in 2019 to 27,382 in 2024 - a difference of 41.5%. For other facilities, other types of buildings have been understood as not included in the various types of buildings listed. However, data from the last year indicate a possible stabilisation. Table 1 shows the differences between building permits issued for Poland in terms of various types of structures, from residential buildings to roads, telecommunications, and water structures. Based on data in Table 1, downward trends were observed in 2021–2023, when Poland was affected by the global economic crisis. However, the values for 2024 show an increase, which means the reconstruction of the country's economy and a desire to return to pre-crisis values.

Table 2 shows a similar summary as Table 1, but divided into regions of Poland in 2019 and 2024, and the reference year is 2019. Based on data in Table 2 in 2019, the lowest number of permits in the total number of buildings category was recorded in south-west Poland, which was also the case in 2024. The highest values in both years were recorded in the central region. The percent change for 2024 compared to 2019 for the central region is 14.8% for total buildings. This phenomenon can be linked to the concentration of capital, the higher rate of urbanisation, and the presence of Warsaw, the largest construction market in Poland. However, the percent change for the north-west region is the highest value, at 31%. It shows the decrease in values, but it means the country is rebuilding after the global crisis. In the case of CA, the values remain low in both years, which is due to the limited number of investments carried out in closed areas. The highest values in this category were recorded in eastern Poland, which may be related to the larger number of military facilities and border infrastructure.

In central Poland, a decrease of 72.5% was recorded compared to 2019, while in southern Poland, there is only a 12.8% decline. The lowest values in both years were recorded in the south-western region for single-family buildings. Central Poland saw an increase of 3%, and the highest decline for the north-west of Poland was 23.6%. For multi-family buildings in 2024, the highest number was recorded in central Poland, but it increased for the whole of Poland. The smallest values were observed for the north-west of Poland,

and the percentage change was 14.2%. This increase can be linked to the intensification of residential investment in the Warsaw agglomeration and other large cities in central Poland. In the case of collective residential buildings, hotels, and accommodation buildings, the lowest value in 2019 was recorded in the south-west, with 103 permits. In 2024, the central region recorded only 62 permits. However, the largest percentage increase in 2024, compared to 2019, was recorded in the south-west of Poland, at 139.8%. The rise in the central region can be explained by the highest concentration of tourist facilities compared to coastal and mountain regions.

Table 2. Number of building permits issued for specific types of buildings in Poland in 2019 and 2024 by region and percentage rate

Region	TB	CA	SB	MB	RB	PB	FB	IWB	TF	WS	PP	OF
Year 2019												
Central	49 632	138	23 596	1 805	200	1 566	4 115	1 220	745	25	5 477	10 883
South	44 897	117	23 131	2 016	221	2 152	1 575	900	541	51	4 775	9 985
East	44 761	240	19 953	656	325	1 875	4 203	1 063	593	72	5 827	10 194
South-west	18 695	90	10 653	1 419	103	946	494	552	395	43	2 336	1 754
North-west	44 350	194	20 204	2 830	761	2 639	2 192	1 508	1 005	159	6 020	7 032
North	33 903	170	16 104	2 177	321	1 417	1 449	941	593	72	3 890	6 939
Year 2024												
Central	42 271	38	24 312	3 691	62	1 718	2 606	1117	525	19	1 632	6 589
South	35 057	102	20 055	2 675	353	2 005	1 405	963	674	35	1 405	5 487
East	32 845	199	17 074	1 626	279	1 719	2 772	843	619	63	1 497	6 353
South-west	15 965	63	8 925	2 401	247	951	442	518	232	27	1 308	914
North-west	30 587	96	15 428	3 233	536	2 092	1 428	1 045	873	89	1 702	4 161
North	25 838	84	13 488	2 621	545	1 366	1 043	860	460	69	1 508	3 878
Rate [%]												
Central	−14.8	−72.5	3.0	104.5	−69.0	9.7	−36.7	−8.4	−29.5	−24.0	−70.2	−39.5
South	−21.9	−12.8	−13.3	32.7	59.7	−6.8	−10.8	7.0	24.6	−31.4	−70.6	−45.0
East	−26.6	−17.1	−14.4	147.9	−14.2	−8.3	−34.0	−20.7	4.4	−12.5	−74.3	−37.7
South-west	−14.6	−30.0	−16.2	69.2	139.8	0.5	−10.5	−6.2	−41.3	−37.2	−44.0	−47.9
North-west	−31.0	−50.5	−23.6	14.2	−29.6	−20.7	−34.9	−30.7	−13.1	−44.0	−71.7	−40.8
North	−23.8	−50.6	−16.2	20.4	69.8	−3.6	−28.0	−8.6	−22.4	−4.2	−61.2	−44.1

TB – total number of buildings, CA – including those in closed areas, SB – single-family buildings, MB – multi-family buildings, RB – collective residential buildings, hotels, and accommodation buildings, PB – public utility buildings, FB – farm buildings and livestock buildings, IWB – industrial and warehouse buildings, TF – transport infrastructure facilities, WS – water structures, PP – pipelines, telecommunications and power lines, OF – other facilities.

Central: Łódzkie voivodeship, Mazowieckie voivodeship; South: Małopolskie voivodeship, Śląskie voivodeship; East: Lubelskie voivodeship, Podkarpackie voivodeship, Świętokrzyskie voivodeship, Podlaskie voivodeship; South-West: Dolnośląskie voivodeship, Opolskie voivodeship; North-West: Wielkopolskie voivodeship, Zachodniopomorskie voivodeship, Lubuskie voivodeship; North: Kujawsko-Pomorskie voivodeship, Warmińsko-Mazurskie voivodeship, Pomorskie voivodeship.

Source: own work based on GUNB (2025).

Furthermore, public utility buildings for the central and south-west regions of Poland recorded an increase, but other parts of Poland recorded a decrease. The highest number was 2,092 permits for the north-west in 2024. Few farm buildings were constructed in Poland from 2019 to 2024, and the decline in 2024 was 36.7% for the central region. Significant decreases were also recorded in the east and north-west of the country, at 34% and 34.9%, respectively. For industrial and warehouse buildings, the highest value of 1,508 permits was recorded in the north-west of Poland in 2019, while in 2024 it was recorded in the central part of the country, at 1,117 permits. The percentage change for the central region was 8.4% and for the north-west of Poland it was 30.7%. For water structures, due to the low level of implementation of this type of investment in Poland, the values remained low – in 2019 they ranged from 25 to 159 permits, and in 2024 from 19 to 89. In both years, the highest results were achieved by the north-west region. For this region, the highest decline was recorded, at 44%.

In the case of pipelines, telecommunications, and power lines, there was a marked decline: in 2019, the highest value was recorded in the northern region, with 6,020 permits, and in 2024, there were 1,702 permits. This decline is related to the end of the intensive development phase of fibre optic networks and telecommunications infrastructure, which took place in 2019.

In 2019, for other facilities, the highest number was 10,883 permits for central Poland, and the lowest was for the south-west of Poland, with 1,754 permits. In 2024, central Poland maintained its leading position with 6,589 permits, while the lowest result was recorded in the south-west, with 914 permits. For the whole of Poland, compared 2019 to 2024, a decrease was observed for other facilities. In summary, in terms of TB and CA, central Poland continues to have a clear investment advantage, while the south-west consistently records the lowest values. Regional differences are mainly due to population density, availability of development land, economic specifics of regions, and proximity to large urban regions.

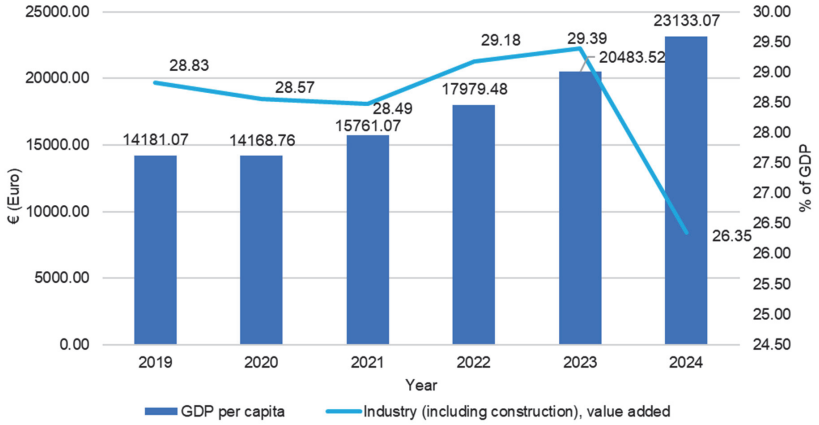
Poland, as the reference country, was subjected to a detailed analysis based on data obtained from the statistical office on building permits issued in 2019–2024. Another analysis compares Poland and four selected countries in macroeconomic terms in terms of the percentage share of the construction sector in GDP and GDP per capita for all selected countries.

Macroeconomic characteristics of selected countries

This chapter presents the macroeconomic values of selected European countries based on GDP per capita, with Poland serving as the basis for selecting countries with lower and higher GDP than Poland. The data selection was made based on 2019, which serves as the reference year for further analysis. The analysis focuses on GDP at current market prices and the value added of the industrial sector in 2019–2024. These two indicators provide insight into the overall economic condition and the role of industry in national economies, which are essential for understanding the conditions affecting the construction sector. The first analysis is for Poland from 2019 to 2024, and the values for this period are shown in Figure 5.

Between 2019 and 2024, Poland significantly increased its GDP per capita from 14,181.07 EUR in 2019 to 23,133.07 EUR in 2024. The decline in 2022 was due to several global events that occurred in the years selected for analysis: the lingering effects of the COVID-19 pandemic, supply problems, a sharp rise in energy prices following Russia's aggression against Ukraine, as well as high inflation, which exceeded 14% in 2022. The share of industry (including construction) in GDP remained relatively stable between 2019 and 2023, at 28.8% and 29.4% respectively. This means that the industrial sector maintained its position in the economy despite global crises. In 2024, however, there was a sharp decline to 26.4%. This was due to, among other things, a reduction in exports due to the slowdown, a decrease in production in energy-intensive industries due to high energy costs, increases in interest rates on loans, and labour shortages in construction and industry, partly due to the return of Ukrainian citizens to their country. Despite these problems, the record GDP per capita in 2024 shows that Poland wants to develop and achieve even better results in the future. However,

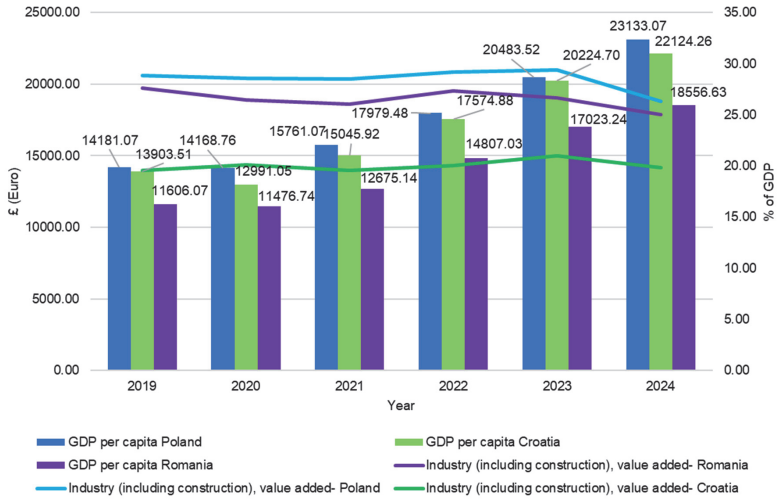
the structure of the economy is changing, and the share of industry is declining. Croatia and Romania are other countries chosen for analysis. Figure 6 shows a comparison of GDP per capita for Poland, Croatia, and Romania in 2019–2024 and the share of industry in their GDP.



The values presented in Figure 5 in euros have been converted using the weighted average exchange rate for each year separately: 2019: 1 USD = = 0.893 EUR; 2020: 1 USD = 0.877 EUR; 2021: 1 USD = 0.846 EUR; 2022: 1 USD = 0.952 EUR; 2023: 1 USD = 0.925 EUR; 2024: 1 USD = = 0.924 EUR. The conversion is based on historical data from the National Bank of Poland on 17 September 2025 (NBP, 2019–2024).

Fig. 5. Comparison of gross domestic product per capita and industry (including construction) values for Poland in 2019–2024

Source: own work based on WB (2025).



The values presented in Figure 6 in euros have been converted using the weighted average exchange rate for each year separately: 2019: 1 USD = = 0.893 EUR; 2020: 1 USD = 0.877 EUR; 2021: 1 USD = 0.846 EUR; 2022: 1 USD = 0.952 EUR; 2023: 1 USD = 0.925 EUR; 2024: 1 USD = = 0.924 EUR. The conversion is based on historical data from the National Bank of Poland on 17 September 2025 (NBP, 2019–2024).

Fig. 6. Comparison of gross domestic product per capita and industry (including construction) values for Poland, Croatia, and Romania in 2019–2024

Source: own work based on WB (2025).

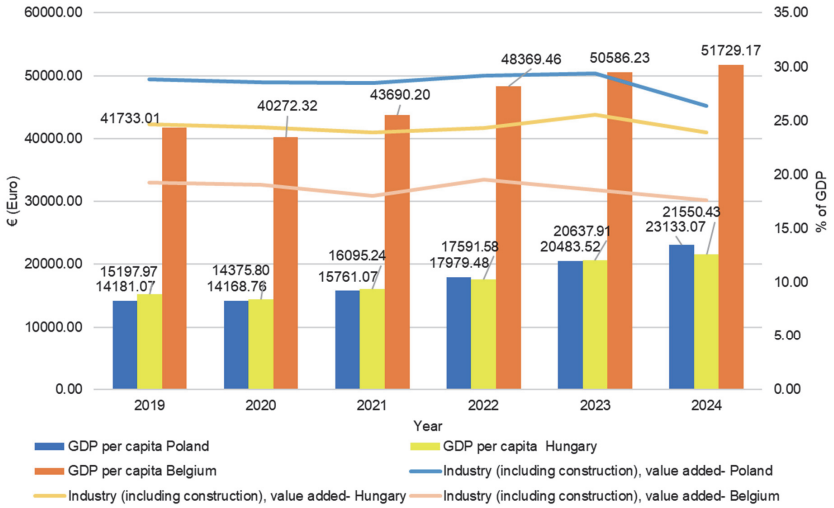
Figure 6 presents a comparison of countries such as Poland, Croatia, and Romania. Between 2019 and 2024, Poland's GDP values showed an upward trend with low growth in 2020 of about 1% compared to 2019. However, it can be seen that the other two countries, Croatia and Romania, recorded lower values than Poland, but also showed an upward trend.

In the case of Croatia's GDP, the only decline was recorded in 2020 to 12,991.05 EUR. The decline was caused by the COVID-19 pandemic, which led to lockdowns across almost all of Europe and the world. This resulted in, among other things, travel restrictions, limited workplaces, and a large number of cases and deaths at that time. In 2021, when the restrictions were lifted and tourist traffic was unblocked, Croatia's GDP rebounded to 15,045.92 EUR. This result was even higher than the pre-pandemic values. In addition, Croatia, as a member of the EU, received a lot of funding at that time, and the number of new investments increased, and external consumption improved. Furthermore, in 2023, Croatia joined the eurozone, which increased its financial stability (Barbić, 2024). The situation in Romania was similar to that in Croatia, but the lowest value recorded for 2019 was 11,606.07 EUR. Although Romania is not as dependent on tourism as Croatia, the COVID-19 pandemic affected the industrial, transport, and service sectors, slowing down the economy, and GDP per capita growth in 2021 was not significant, amounting to less than 1% compared to 2020. The following years saw a significant upward trend to 14,807.03 EUR. Romania restarted every economic sector and rebuilt its economy after years of COVID-19, disrupted supply chains, and lockdowns (Moridian et al., 2025).

The contribution of industry (including construction) to GDP varied significantly between countries, but all three countries saw a decline between 2019 and 2021, followed by an upward trend. For Poland, the highest value was achieved in 2023, when the country recovered from the COVID-19 pandemic and the war in Ukraine. This year was also a year of recovery after the interest rate cuts in 2022 and the highest construction costs in 2022–2023. In Croatia, the highest value was recorded in 2023. Tourism returned to its original track after the pandemic, and other global conflicts had no impact. In Romania, growth was already evident in 2022. The country rebuilt its industry and transport sectors, which allowed it to rebound after the pandemic decline. However, after significant growth for each country, declines to pre-pandemic values were already recorded in 2024. It can be concluded that each country's economy is returning to normal after years of struggling with the global pandemic. The figure also shows the share of industry (including construction) in the country's GDP. As can be seen, each of them is at a high level. For Poland, the average values are 30%. For Romania, the value is lower, but it amounts to 26%, with a significant increase to 29% in 2023. In the case of Croatia, the values are significantly lower than those of Poland and Romania. The average value is 18% with an increase to 20% in 2023. The same comparison was made for Poland, Hungary, and Romania, as shown in Figure 7.

Figure 7 shows a comparison of Poland, Hungary, and Belgium in terms of GDP per capita and the contribution of industry (including construction) to GDP as a percentage. Poland, as the country with the lowest GDP among the selected countries, recorded an upward trend in the analysed years. However, the increase in 2019–2020 was only 1%.

In the case of Hungary, there is no clear downward or upward trend. In 2020, the value was 15,197.97 EUR, but this was higher than in 2019 and 2021. The decline was caused by the COVID-19 pandemic, which introduced many restrictions, contributing to the slowdown of the automotive industry, which is one of the pillars of the country's economy. The following years saw a decline in 2022 to a value of 17,591.58 EUR and growth in 2023 to a value of 20,637.91 EUR. Such fluctuations show that Hungary is rebuilding its economy through domestic consumption and exports of automotive parts and cars. However, the energy crisis in Europe in 2023 and weakening foreign demand slowed down the country's economy. In 2024, the situation begins to stabilise, and the values are higher than in 2019 (Petrova & Sznajder Lee, 2024).



The values presented in Figure 7 in euros have been converted using the weighted average exchange rate for each year separately: 2019: 1 USD = = 0.893 EUR; 2020: 1 USD = 0.877 EUR; 2021: 1 USD = 0.846 EUR; 2022: 1 USD = 0.952 EUR; 2023: 1 USD = 0.925 EUR; 2024: 1 USD = = 0.924 EUR. The conversion is based on historical data from the National Bank of Poland on 17 September 2025 (NBP, 2019–2024).

Fig. 7. Comparison of gross domestic product per capita and industry (including construction) values for Poland, Hungary, and Belgium in 2019–2024

Source: own work based on WB (2025).

Belgium, the country with the highest GDP per capita in the period 2019–2024 from the chosen countries, also recorded declines. The first was in 2020, to a level of 40,272.32 EUR, caused by the COVID-19 pandemic. The decline was due to restrictions in the industrial sector, factory shutdowns, and reduced activity in international trade. The year 2021 saw a renewed increase to 43,690.20 EUR. The following years, to 2024, showed an increase. The increase was due to the economic recovery after the pandemic, particularly in exports, and financial support from the EU. The year 2022 saw an energy crisis and high inflation in the country, which contributed to a decline in GDP per capita. Despite the unfavourable economic conditions, 2024 saw a significant increase in value to the highest figure in the analysed years, which was 51,729.17 EUR. The increase is due to the service sector and growing investments in digital technologies and green energy (Minne, Piton, Coppens & Warisse, 2021).

Taking into account the contribution of industry (including construction) in GDP in 2019–2024, Belgium recorded the largest increases and decreases in 2020. The lowest value was recorded in 2021, when the country was recovering from the pandemic. In the same year, a decline was recorded for Poland, which was influenced not only by the pandemic but also by the conflict in Ukraine. For Hungary, it can also be noted that 2021 is a year of return to pre-pandemic levels and even higher. Each of the countries owes a significant share of GDP per capita to the industrial sector, which means that the values are inconclusive and do not show specific upward or downward trends resulting from global crises. The figure also shows the share of industry (including construction) in the country's GDP. As can be seen, each of them is at a high level. For Poland, the average values are 30%. For Hungary, the value is lower, but it amounts to 22%, with a significant increase to 25% in 2023. In the case of Belgium, the values are significantly lower than those of Poland or Hungary. The average value is 17% with an increase to 20% in 2023 and a decrease in 2021 to 15%.

Comparative analysis of Poland versus selected countries based on the construction sector

Croatia

The first country analysed with a GDP similar to Poland's is Croatia. Figure 8 shows a comparison of the number of building permits issued in Poland and Croatia in 2019–2024.

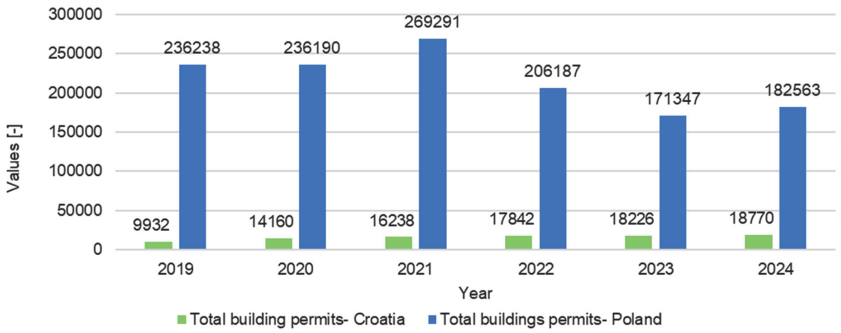


Fig. 8. Total building permits in Poland and Croatia in 2019–2024

Source: own work based on the Croatian Bureau of Statistics [DZS] (2025).

Total building permits include the total number of building permits issued for residential buildings and civil engineering work in 2019–2024. Data analysis shows that during the period under review, the total number of building permits issued in Poland was significantly higher than in Croatia, but was characterised by greater volatility. In Poland, there was no clear trend: values grew in subsequent years, only to decline thereafter. In 2019, the number was 236,238 permits, but in 2020, it was lower at 236,190 building permits. The highest result was achieved in 2021, with 269,291 building permits, which coincided with the initial period of the COVID-19 pandemic in Europe. The following years brought significant declines: in 2022 to 206,187, and in 2023 to 171,347, which represents a 27.5% decrease compared to 2019. It was not until 2024 that a rebound was recorded, which is related to both the post-pandemic recovery process and the adjustment of the economy to the effects of the war in Ukraine, which began in February 2022. The value for 2024 was 182,563 building permits. The construction market was affected by, among other things, staff shortages caused by the emigration of workers from Ukraine, disruptions in material supply chains, and high inflation limiting access to financing (Wieczorek & Dzięcioł, 2025).

In Croatia, the dynamics were different. An upward trend was observed in the years analysed, from 9,932 building permits in 2019 to 18,770 in 2024, representing an increase of 89% compared to the base year. From 2019 to 2024, the number of building permits increased each year: 14,160 in 2020, 16,238 in 2021, 17,842 in 2022, and 18,226 in 2023. The construction sector in Croatia showed greater stability despite global economic shocks. The COVID-19 pandemic in 2020 caused a decline in tourist activity, especially in the Adriatic region, but thanks to effective macroeconomic policies, including wage subsidies, liquidity lines, and job protection, the economy recovered quickly. Already in 2021, Croatia had public and private investment in construction that was supported by EU funds and the actions of the Croatian Bank for Reconstruction and Development. Exchange rate stability and inflation control further strengthened the position of investors (Bank for Reconstruction and Development [HBOR], 2021).

Comparing the two countries, it can be concluded that Poland, despite the larger scale of investment, showed greater vulnerability of the construction sector to crisis factors, in particular, supply disruptions and labour outflows. Croatia, on the other hand, thanks to its smaller market size, strong state support, and rapid implementation of stabilisation programmes, maintained a consistent upward trend in the number of building permits issued.

Poland, as a Central European country, is not as dependent on tourism as Croatia, especially its Adriatic coast, which is one of the most important tourist destinations in Europe. The following analysis regards residential buildings. An analysis of the data in Figure 9 shows significant differences in the number of building permits issued only for residential buildings.

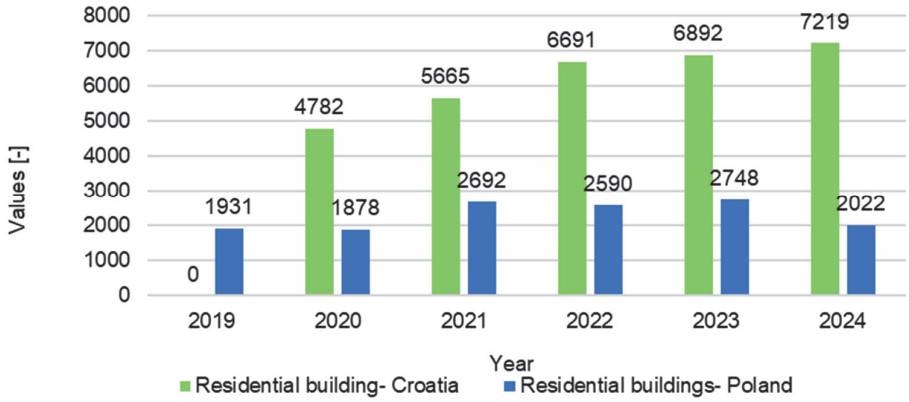


Fig. 9. Residential building permits in Poland and Croatia in 2019–2024

Source: own work based on DZS (2025).

For Poland, residential buildings include collective residential buildings, hotels, and accommodation facilities. For Croatia, however, there is no available information on what this category comprises, but there are many types of residential buildings with a roof, based on data from Eurostat. Moreover, no data is provided for 2019. This fact results from the statistical system and the possibility of presenting results by country. Despite uniform European standards, each country provides data with its own specific characteristics and access to it. Between 2019 and 2024, Croatia saw a clear upward trend, with the number of building permits rising from 4,782 in 2020 to 7,219 in 2024. This increase is a consequence of growing tourist demand and investments in accommodation infrastructure, supported by EU funds and national tourism development programmes. Croatia has been consistently developing its accommodation base since 2019, and during the COVID-19 pandemic, it introduced a number of protective measures, including wage subsidies and financial liquidity support for businesses. This made it possible to avoid a sharp decline in investment in the hotel sector and maintain the pace of growth in subsequent years (Mikulić, Kečeк & Žajdela Hrustek, 2023).

In Poland, no such significant changes were observed in the residential buildings category during the period analysed. There was an upward trend in 2019–2021 from 1,931 to 2,692 building permits, but 2022 brought a decline to 2,590, followed by an increase to 2,748 in 2023, and in 2024, there was another decline to a level similar to that of 2022. The limited demand for new investments in this segment in Poland results from the lower importance of tourism in the economy and the large number of existing facilities of this type.

In addition, in 2020–2021, due to the pandemic, travel restrictions were introduced, many tourist facilities were closed, and the demand for accommodation fell sharply. As a result, many projects to build new hotels or resorts have been suspended or postponed to subsequent years (Pazdzior, Sokol & Styk, 2021). The following analysis was made based on Figure 10, which shows a significant difference in the scale of investment in transport infrastructure facilities between Poland and Croatia. In Poland, the number of building permits issued in the analysed period was counted in thousands, while in Croatia, in hundreds.

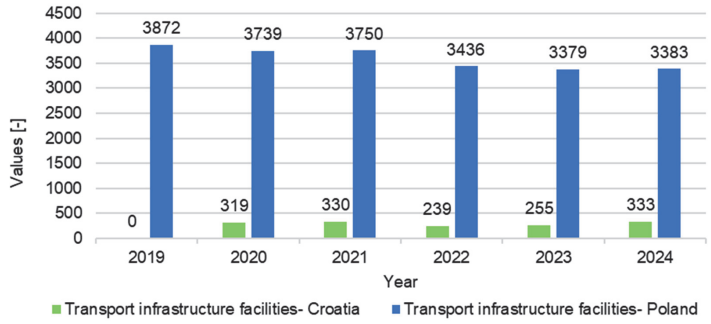


Fig. 10. Transport infrastructure facility permits in Poland and Croatia in 2019–2024

Source: own work based on DZS (2025).

For Poland, transport infrastructure facilities include roads, bridges, viaducts, waterways, and even airports. For Croatia, based on Eurostat data, these are other civil engineering works intended for the movement of vehicles, ships, aircraft, people, or animals. Furthermore, for Croatia, open access has only been available for the last 5 years, so for 2019, we have no data. This fact results from the statistical system and the possibility of presenting results by country. Despite uniform European standards, each country provides data with its own specific characteristics and access to it. Between 2019 and 2024, Poland saw a decline in the number of building permits from 3,872 to 3,383, with 2021 being an exception, when the number of building permits rose to 3,750. The lowest was for 2023, with 3,379 building permits. The development of transport infrastructure in Poland during this period was linked to the implementation of several large projects, such as the commissioning of 163 km of the S17 expressway, the expansion of connections with smaller towns to the S12 route, and the modernisation and expansion of the tram network in Warsaw. In addition, the construction of the Central Communication Port, scheduled to open in 2032, was planned. The high scale of investment is due, among other things, to access to EU funds, including funds from infrastructure programmes and the Cohesion Fund.

In Croatia, no uniform trend emerged during the same period. An increase was recorded in 2021, with 330 building permits, followed by a decline to 239 building permits in 2022, a consequence of the economic slowdown related to the COVID-19 pandemic, and another increase to 333 building permits in 2024. The lowest value recorded for 2022 was 239 building permits. The development of the transport infrastructure in Croatia is based on the implementation of the Transport Development Strategy 2017–2030, which aims to modernise the neglected road and rail network and build new connections to improve the country's transport cohesion. In addition, as part of the Green Infrastructure programme, financed in part by the European Investment Bank (EIB), Croatia is implementing projects supporting green mobility, the digital transformation of the transport sector, and the reduction of greenhouse gas emissions (Ministry of Maritime Affairs, Transport and Infrastructure of Croatia [MMPI RH], 2025).

In summary, Poland has significantly greater financial resources and a broader portfolio of infrastructure projects, which allows it to maintain a high level of investment. Croatia, although operating on a smaller scale, has consistently increased its spending on transport development in recent years, and the increase in the number of building permits in 2024 may signal a further acceleration in the implementation of road and rail projects.

Romania

Romania is the second country with a GDP lower than that of Poland selected for analysis. In Poland, however, residential buildings comprise a sum of single-family buildings, multi-family buildings, collective residential buildings, hotels and accommodation facilities, public utility buildings, farm and livestock buildings, as well as industrial and warehouse buildings. For Romania, however, there is no available information on what this category comprises. Still, based on data from Eurostat, there are buildings inhabited by people. Despite uniform European standards, each country offers data with specific characteristics and access. For Romania, no data is available for 2019. This fact results from the statistical system and the possibility of presenting results by country. The data obtained is not as detailed as in the case of Poland. Still, it is sufficient to perform a macroeconomic analysis of the construction sector based on building permits issued (Fig. 11).

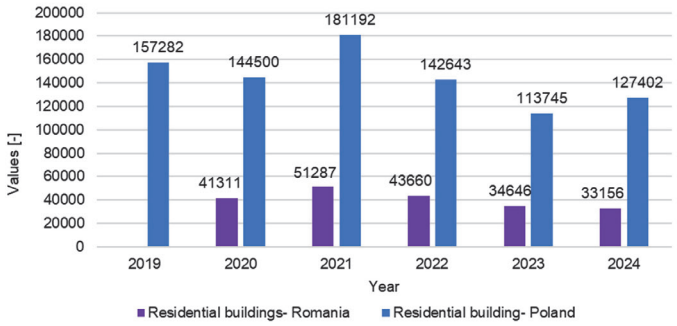


Fig. 11. Residential building permits in Poland and Romania in 2019–2024

Source: own work based on the National Institute of Statistics – Romania [INSSE] (2025).

In Romania, the values in the category of residential buildings are significantly lower than in Poland. The highest level was recorded in 2021, with 51,287 building permits. Two clear trends can be distinguished in the analysed period: an increase in 2020–2021 from 41,311 to 51,287 building permits, followed by a decline in 2022–2024 from 43,660 to 33,156 building permits. Romania's economic development in the years preceding the COVID-19 pandemic was hampered by sanitary restrictions and limitations on economic activity, which significantly affected the construction sector. Despite the government's implementation of financial support programmes for households and businesses, the economic recovery process has been gradual, which is reflected in the downward trend after 2021 (Radulescu et al., 2020). In Poland, the number of building permits issued in the same category was at its highest level in 2021. There were 181,192 building permits, which represents an increase of 23,910 compared to 2019. Unlike Romania, there is no uniform downward or upward trend in Poland. After a dynamic growth in 2021 to a value of 181,192 building permits, there was a sharp decline to 113,745 building permits in 2023, but 2024 showed an increase to 127,402 building permits. However, Poland is characterised by a much larger investment scale than Romania. The difference is particularly in multi-family housing, farm buildings, industrial buildings, and public facilities. This is due to both a larger population and a higher level of urbanisation and access to more significant investment funds (Fig. 11).

For Poland, however, non-residential buildings comprise transport infrastructure facilities, water structures, pipelines, telecommunications, and power lines, as well as other facilities. For Romania, non-residential buildings are all types of civil engineering works that are not for the permanent residence of people. Despite uniform European standards, each country provides data with its own specific characteristics and access to it. For Romania, no data is available for 2019. This fact results from the statistical system and the possibility of presenting results by country. The data obtained is not as detailed as in the case of Poland, but it is sufficient to perform a macroeconomic analysis of the construction sector based on building permits issued (Fig. 12).

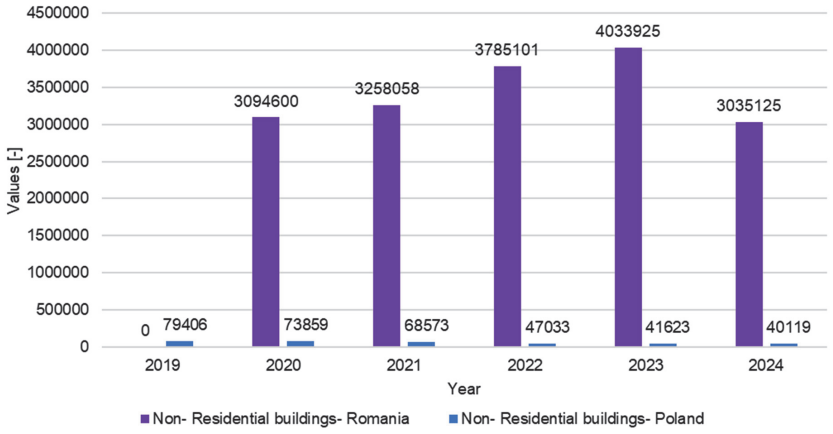


Fig. 12. Non-residential building permits in Poland and Romania in 2019–2024

Source: own work based on INSSE (2025).

Data analysis shows that in Romania, the number of building permits issued in non-residential buildings significantly exceeds the figures recorded in Poland. Between 2020 and 2023, a clear upward trend was observed from 3,094,600 building permits in 2020 to the highest level reached in 2023, with 4,033,925 building permits. However, in 2024, there was a sharp decline to 3,035,125 building permits from the previous year. Despite maintaining growth during the COVID-19 pandemic, the decline in 2024 may result from the slowdown in significant public investments and budgetary and investment policy changes. During the crisis, Romania maintained a similar level of non-residential construction. The country's economic policy influenced this, with fewer restrictions during the crisis, as well as by the income needs of residents. No upward trend was observed in Poland. The highest value was recorded in 2019, at 79,406. The following years coincided with the most significant wave of COVID-19 infections, with building permits declining to 73,859. In 2022, there was a decline to 47,033 building permits. The lowest result in the analysed period was reached in 2024 with 40,119 building permits. At that time, the Polish economy was strongly affected by the COVID-19 pandemic and the effects of the war in Ukraine, which slowed down the pace of investment. The reconstruction of the construction sector is still ongoing, and a return to the level of 2019 depends on the stabilisation of the country's macroeconomic situation (Fig. 12).

Hungary

The first country selected for analysis with a GDP higher than that of Poland is Hungary. Figure 13 compares the number of building permits issued for residential buildings in Poland and Hungary between 2019 and 2024.

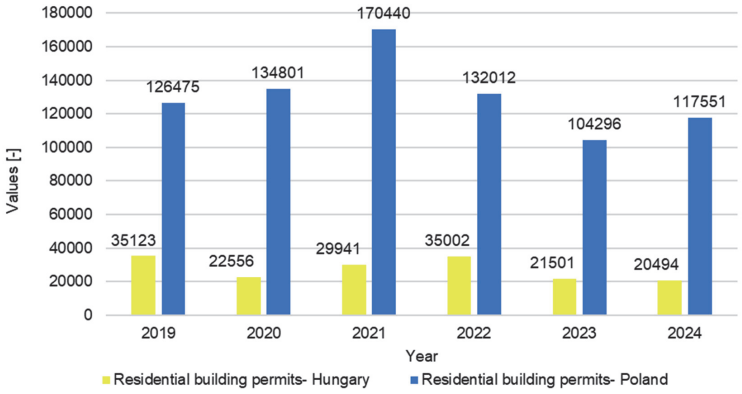


Fig. 13. Permits for residential buildings in Poland and Hungary in 2019–2024

Source: own work based on the Hungarian Central Statistical Office [KSH] (2025).

In Poland, residential buildings comprise a sum of single-family buildings, multi-family buildings, collective residential buildings, hotels, and accommodation facilities. For Hungary, however, there is no available information on what this category comprises, but there are many types of residential buildings with a roof, based on data from Eurostat. This fact results from the statistical system and the possibility of presenting results by country. Despite uniform European standards, each country provides data with its own specific characteristics and access to it. This fact results from the statistical system and the possibility of presenting results by country. The data obtained is not as detailed as in the case of Poland, but it is sufficient to perform a macroeconomic analysis of the construction sector based on building permits issued. The total number of building permits in Poland in the analysed period was significantly higher than in Hungary. Between 2019 and 2021, there was an increase from 126,475 to 170,440 building permits, and then a decline to the lowest value of 104,296 in 2023. This decline was due to restrictions related to the COVID-19 pandemic, which affected both office and manual workers, and the consequences of the war in Ukraine, which caused an outflow of some construction workers who had previously come to Poland for economic reasons. In 2024, there was an increase to 117,551 building permits, which can be interpreted as the beginning of the Polish construction sector's return to pre-pandemic levels.

In Hungary, there was an increase in the number of building permits between 2020 and 2021, from 22,556 to 29,941, indicating a significant investment revival during this period. Then, there was an increase to 35,002 in 2022 and a decrease to 21,501 building permits in 2023. The value for 2024 was 20,494 building permits. However, in 2019, the number was the highest, with 35,123 building permits. However, when analysing the chart, it can be seen that Poland, as a country with a lower GDP per capita, has a significantly higher share of building permits issued than Hungary because the Polish economy is based on construction. Hungary is a country with an economy focused on tourism, trade, and industry. Residential construction dominates, but most new investments are public investments.

Belgium

The last country selected for analysis is Belgium, whose GDP is significantly higher than Poland's. Figure 14 shows a comparison of the number of building permits issued for residential buildings in Poland and Belgium between 2019 and 2024. In Poland, residential buildings comprise a sum of single-family buildings, multi-family buildings, collective residential buildings, hotels and accommodation facilities, public utility buildings,

farm and livestock buildings, as well as industrial and warehouse buildings. For Belgium, there is no available information on what this category comprises, but there are many types of buildings inhabited by people, based on data from Eurostat. Despite uniform European standards, each country provides data with its own specific characteristics and access to it. This fact results from the statistical system and the possibility of presenting results by country. The data obtained is not as detailed as in the case of Poland, but it is sufficient to perform a macroeconomic analysis of the construction sector based on building permits issued.

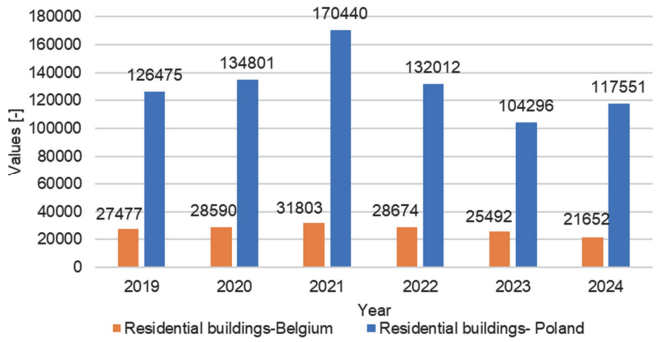


Fig. 14. Residential building permits in Poland and Belgium in 2019–2024

Source: own work based on Statistics Belgium [Statbel] (2025).

In Poland, the number of building permits issued increased between 2019 and 2021 to 170,440, and then declined, reaching its lowest point in 2023 to 104,296. The year 2024 marks a rebound after the pandemic, lockdown, and normalisation of relations in Ukraine, as shown by the increase in the figure to 117,551 building permits. In the case of Belgium, there is also a significant upward trend in 2019–2021, from 27,477 to 31,803 building permits. The following years registered a decline to the lowest value achieved in 2024, to 21,652 building permits. The COVID-19 pandemic significantly disrupted the construction sector, leading to worker shortages, delays in material supplies, and economic instability. This contributed to a noticeable decline in issued building permits for dwellings during the 2021–2023 period (Minne et al., 2021). Comparing the two countries, Poland maintained a significantly higher level of building permits issued for residential buildings than Belgium during the period analysed. Despite this, the impact of the COVID-19 pandemic and subsequent external and internal factors in both countries after 2021 is evident in both cases. Belgium is a country focused on services such as trade, finance, logistics, and international administration. Therefore, its strong industries are chemicals, pharmaceuticals, food, and information technology. Despite the high demand for residential buildings, the construction of public utility buildings, administration, industry, and logistics plays an important role.

Between 2019 and 2024, Poland maintained a high number of building permits issued compared to the other countries analysed. Despite the COVID-19 pandemic and the war in Ukraine, which caused declines after 2021, each country began to rebuild, and these changes are visible in 2024. Croatia, heavily dependent on tourism, quickly rebuilt its construction sector thanks to state financial support. Romania maintained high permit values until 2023, but in 2024, there was a marked decline despite public investment. In Hungary, the number of building permits grew between 2020 and 2022, but their values were significantly lower than in Poland. Hungary focused on tourism, trade, and industry, but in Poland, the main sector of the economy is the construction sector. Belgium, as the country with the highest GDP, also recorded growth until 2021, followed by a decline of more than 21% compared to 2019, without detailed data on the types of buildings. The country is focused on industry and services, with construction accounting for a large share of its GDP.

CONCLUSIONS

This article focuses on the construction sector in four selected countries compared to Poland. The countries were selected based on an analysis of GDP per capita in 2019, namely the reference year. Romania and Croatia were chosen as two countries with a lower GDP per capita than that of Poland, while Hungary and Belgium were chosen as countries with a higher GDP per capita than that of Poland. The analysis was carried out for all selected countries, using Poland as the reference point, and covered the number of building permits issued for residential buildings, non-residential buildings, transport infrastructure facility permits, and total building permits. The main indicator analysed in the article was the number of building permits issued between 2019 and 2024. These years were marked by global crises such as the COVID-19 pandemic and the war in Ukraine. These are likely factors influencing the number of building permits issued and the macroeconomic situation of the countries selected for analysis.

In Poland, the total number of building permits increased between 2019 and 2021, with the highest number recorded at 269,291 building permits. Then, in 2022 and 2023, there was a sharp decline. In 2024, there was a rebound, but the results remained lower than in 2021.

In Croatia, the trend for the total number of buildings was more stable. From 2019 to 2024, there was an increase to the highest number of 18,770 permits in 2024. Moreover, the trend for residential buildings was the same, with the highest number recorded in 2024. The highest number for transport infrastructure facilities was in 2021, with 330 building permits. This means a significant decline in the subsequent years due to the coronavirus pandemic, lockdowns, and restrictions on movement.

In Romania, the number of non-residential building permits was high between 2020 and 2023, with the highest value being 4,033,925 building permits. However, for residential buildings, the values were significantly lower, with the highest number recorded in 2021, at 181,192 building permits.

In Hungary and Belgium, the changes were smoother. Belgium had a more stable construction sector than Poland. The highest number was 170,440 building permits in 2021. For Hungary, the highest number was the same as in Belgium in 2021. In addition, the analysis showed how the economies of selected European countries developed between 2019 and 2024, highlighting downward and upward trends. It also showed how each of the selected countries coped with global crises such as the COVID-19 pandemic.

The data contained on the websites of statistical offices or Eurostat did not show the same level of detail as for Poland; therefore, data aggregators were used to obtain more data for analysis. In addition, data for Croatia and Romania for 2019 were not made available by the statistical offices. Despite the lack of detailed data from national statistical offices, Eurostat data and its building type dictionary were used as a basis. Based on information from Eurostat, residential buildings are structures that have a roof, but not necessarily walls, and are intended for permanent human habitation, while non-residential buildings are all types of buildings that are not intended for permanent human habitation. Additionally, there are other civil engineering works designed for the movement of vehicles, ships, aircraft, people, or animals. Total building permits include the total number of building permits issued for residential buildings and civil engineering work.

Another problem was the lack of currency standardisation for GDP per capita for selected countries. The values were determined using average annual exchange rates for each year from 2019 to 2024, based on rates provided by the National Bank of Poland. The data was converted from USD to EUR based on the designated average annual exchange rates. This conversion allowed for the standardisation of the collected values and the performance of detailed analyses.

Despite the problems encountered, a macroeconomic analysis of European countries was carried out to show how each of them fared before, during, and after the global crisis, based on the construction sector and building permits issued. The analysis leaves space for its continuation for European countries in terms of the construction sector. If the data were harmonised to European standards, it could then be collected and used to create models and forecast economic changes in countries based on changes in the construction sector.

Authors' contributions

Conceptualisation: K.W. and J.D.; methodology: K.W.; formal analysis: K.W. and J.D.; investigation: K.W.; resources: K.W.; data curation: K.W.; writing – original draft preparation: K.W.; writing – review and editing: K.W.; visualisation: K.W.; supervision: J.D.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Amca, Y., Yorucu, V. & Kırıkkaleli, D. (2025). Construction Cost Index: Political, Economic, and Financial Risk Indices Within the European Continent. *Sustainability*, *17* (3), 917. https://doi.org/10.3390/su17030917

Attinasi, M. G., Balatti, M., Mancini, M. & Metelli, L. (2025). Supply chain disruptions and the effects on the global economy. *ECB Economic Bulletin*, *8*. Retrieved from: https://www.ecb.europa.eu/press/economic-bulletin/focus/2022/html/ecb.ebbox202108_01~e8ceebe51f.en.html?utm_source=chatgpt.com [accessed: 29.08.2025].

Balakrishnan, R., Rabier, L., Ebeke, C., Firat, M., Malacrino, D. & Rabier, L. (2022). Regional Disparities in Europe. *Working Paper*, *2022/198*. https://doi.org/10.5089/9798400219184.001

Bank for Reconstruction and Development [HBOR]. (2021, 14 June). *News: In 2020, HBOR supported entrepreneurs with an amount of HRK 8 billion and approved 43% of all COVID loans in the Croatian market*. Retrieved from: https://www.hbor.hr/in-2020-hbor-supported-entrepreneurs-with-an-amount-of-hrk-8-billion-and-approved-43-of-all-covid-loans-in-the-croatian-market/55?utm_source=chatgpt.com [accessed: 17.09.2025].

Barbić, T. (2024). Impact of Tourism Activity on Urban Land and Housing Market Activity: Evidence from Croatia. *Economies*, *12* (12), 337. https://doi.org/10.3390/ECONOMIES12120337

Biswas, A., Ghosh, A., Kar, A., Mondal, T., Ghosh, B. & Bardhan, P. K. (2021). The impact of COVID-19 in the construction sector and its remedial measures. *Journal of Physics: Conference Series*, *1797* (1), 012054. https://doi.org/10.1088/1742-6596/1797/1/012054

Brenninkmeijer, A. (2020). *Risks, challenges, and opportunities associated with the EU's economic response to the COVID-19 crisis* (Review 06). European Court of Auditors, Luxembourg.

Cieślik, A. & Turgut, M. B. (2021). Estimating the Growth Effects of 2004 Eastern Enlargement of the European Union. *Journal of Risk and Financial Management*, *14* (3), 128. https://doi.org/10.3390/jrfm14030128

Croatian Bureau of Statistics [DZS]. (2025). *Building Permits*. Retrieved from: https://Podaci.Dzs.Hr/En/Statistics/Construction/Building-Permits [accessed: 29.07.2025].

Czech, K., Karpio, A., Wielechowski, M. & Woźniakowski, T. (2020). *Polska gospodarka w początkowym okresie pandemii COVID-19*. Warszawa: Wydawnictwo SGGW.

Dai, X., Gao, P. & Ma, S. (2024). Cost Forecasting for Building Rebar under Uncertainty Conditions: Methodology and Practice. *Buildings*, *14* (7), 1900. https://doi.org/10.3390/buildings14071900

Dhawan, K., Tookey, J. E. & Poshdar, M. (2024). Lean construction supply chain: A transport perspective. In D.B. Costa, F. Drevland & L. Florez-Perez (Eds.), *Proceedings of the 32nd Annual Conference of the International Group for Lean Construction* (IGLC32) (pp. 979–989). https://doi.org/10.24928/2024/0147

Dutka, P., Stołecka, A. & Janiak, M. (2021). Transparentność w relacjach z kontrahentami na przykładzie spółki Budimex i przedsiębiorstw działających w tej samej branży w latach 2018–2020 oraz w trakcie pandemii COVID-19. *Debiuty Naukowe Studentów Wyższej Szkoły Bankowej*, *21* (21), 47–64.

Eurostat (2025a). *Construction producer price and construction cost indices overview* (online data code: sts_copi_q). Statistics Explained. Retrieved from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Construction_producer_price_and_construction_cost_indices_overview [accessed: 17.09.2025].

Eurostat (2025b). *Glossary: Building*. Statistics Explained. Retrieved from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Building [accessed: 29.08.2025].

Eurostat (2025c). *Glossary: Civil engineering work*. Statistics Explained. Retrieved from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Glossary:Civil_engineering_work [accessed: 17.09.2025].

Eurostat (2025d). *National accounts and GDP* (online data codes: naida_10_gdp; nama_10_gdp). Statistics Explained. Retrieved from: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=National_accounts_and_GDP [accessed: 17.09.2025].

Fernández, J. E. (2020). A Critical Analysis on the European Union's Measures to Overcome the Economic Impact of the COVID-19 Pandemic. *European Papers*, *5* (3), 1399–1423. https://doi.org/10.15166/2499-8249/437

Fredriksson, A., Kjellsdotter Ivert, L. & Naz, F. (2025). Creating logistics service value in construction – a quest of coordinating modules in a loosely coupled system. *Construction Management and Economics*, *43* (6), 428–445. https://doi.org/10.1080/01446193.2025.2449996

Główny Urząd Nadzoru Budowlanego [GUNB]. (2025). Ruch budowlany. Retrieved from: https://www.gov.pl/web/gunb/ruch-budowlany [accessed: 28.07.2025].

Hazam, A. & Ouhna, L. (2024). Resilient Factors of Construction Sector Companies: A Narrative Literature Review. In S.D. Carter, S. Bensal (Eds), *Management and Resilience of African Organizations in Times of Crisis. CBIAC 2023. Springer Proceedings in Business and Economics* (pp. 289–305). Cham: Springer. https://doi.org/10.1007/978-3-031-56007-1_18

Hungarian Central Statistical Office [KSH]. (2025). *Issued dwelling construction permits and construction*. Retrieved from: https://www.ksh.hu/stadat_files/lak/en/lak0006.html [accessed: 30.07.2025].

Kastiukas, G. & Zhou, X. (2019). Green Integrated Structural Elements for Retrofitting and New Construction of Buildings. *IOP Conference Series: Materials Science and Engineering*, *660* (1), 012074. https://doi.org/10.1088/1757-899X/660/1/012074

Kaźmierczak, D. (2021). Znaczenie sektora budownictwa dla krajowej gospodarki w latach 2016–2020. *Nowoczesne Budownictwo Inżynieryjne*, *1* (94), 28–31.

Kraska, E. M. & Kot, J. (2024). Wpływ pandemii koronawirusa na sytuację finansową branży budowlanej. *Przegląd Prawno-Ekonomiczny*, *2*, 75–98. https://doi.org/10.31743/ppe.16606

Leifgen, C. & Kujajewski, S. (22 July 2018). Integrated Digital and Model-Based Construction Logistics Management Based on Lean Thinking Approaches. In *2018 Proceedings of the 35th ISARC, Berlin, Germany* (pp. 428–435). https://doi.org/10.22260/ISARC2018/0060

Licchetta, M. & Mattozzi, G. (2023). Convergence in GDP per Capita in the Euro Area and the EU at the Time of COVID-19. *Intereconomics*, *58* (1), 43–51. https://doi.org/10.2478/ie-2023-0012

Lusztyna, M. (2022). *Polska bankowość w czasie pandemii Covid-19. Wybrane zagadnienia*. Warszawa: Wydawnictwo Centrum Myśli Strategicznych.

Łaszek, J., Olszewski, K. & Augustyniak, H. (2024). How the War between Russia and Ukraine Caused a Multi-Cycle in the Polish Housing Market. *Critical Housing Analysis*, *11* (1), 15–30. https://doi.org/10.13060/23362839.2024.11.1.561

Mikulić, D., Keček, D. & Žajdela Hrustek, N. (2023). Effects of COVID-19 on Adriatic and Continental Croatia tourism: a regional input-output perspective. *Economic Research –Ekonomska Istraživanja*, *36* (2). https://doi.org/10.1080/1331677X.2022.2142811

Ministry of Maritime Affairs, Transport and Infrastructure of Croatia [MMPI RH]. (2025). Government endorses transport development strategy until 2030. Retrieved from: https://mmpi.gov.hr/transport/news-780/government-endorses-transport-development-strategy-until-2030/18888 [accessed: 01.08.2025].

Minne, G., Piton, C., Coppens, B. & Warisse, C. (2021). The Belgian economy in the wake of the COVID-19 shock. *NBB Economic Review*, *September*, 131–157.

Moridian, A., Radulescu, M., Usman, M., Mahdavian, S. M., Hagiu, A. & Serbanescu, L. (2025). Unemployment rate and its relationship with government size, trade, inflation, urbanization, and economic growth in Romania. *Heliyon*, *11* (10), e41579. https://doi.org/10.1016/J.HELIYON.2024.E41579

Mucha-Leszko, B. & Twarowska, K. (2016). The European Union as A Global Economic Power. *Comparative Economic Research. Central and Eastern Europe*, *19* (3), 27–44. https://doi.org/10.1515/cer-2016-0019

Narodowy Bank Polski [NBP]. (2019–2024). *Average exchange rates* (archive). Retrieved from: https://nbp.pl/statystyka-i-sprawozdawczosc/kursy/archiwum-tabela-a-csv-xls/ [accessed: 17.09.2025].

Narodowy Bank Polski [NBP]. (2021). *Senior loan officer opinion survey on bank lending practices and credit conditions 1st quarter 2021*. Warsaw. Retrieved from: https://nbp.pl/wp-content/uploads/2022/10/kredytowy1_2021_en.pdf [accessed: 17.09.2025].

National Institute of Statistics – Romania [INSSE]. (2025). Retrieved from: https://insse.ro/cms/en/search/node/Construction%20permits%20released%20for%20buildings [accessed: 17.09.2025].

Ogunnusi, Hamma-Adama, M., Salman, M. & Kouider, T. (2020). COVID-19 pandemic: the effects and prospects in the construction industry. *International Journal of Real Estate Studies*, *14* (2), 120–128. https://doi.org/10.11113/intrest.v14nS2.71

Pappa, E., Ramos, A. & Vella, E. (2024). Which Crisis Support Fiscal Measures Worked During the Covid-19 Shock in Europe? *SERIEs*, *15* (4), 327–348. https://doi.org/10.1007/s13209-023-00288-w

Pazdzior, A., Sokol, M. & Styk, A. (2021). The Impact of the COVID-19 Pandemic on the Economic and Financial Situation of the Micro and Small Enterprises from the Construction and Development Industry in Poland. *European Research Studies Journal*, *24* (2), 751–762. https://doi.org/10.35808/ersj/2309

Petrova, B. & Sznajder Lee, A. (2024). Integrating with the Global Economy: The Evolution of the Export Profiles of the European Union's Eastern Periphery (2000–2021). *Europe-Asia Studies*, *76* (5), 696–719. https://doi.org/10.1080/09668136.2024.2332671

Pietrzykowski, M. (2019). Convergence in GDP per capita across the EU regions – spatial effects. *Economics and Business Review*, *5* (2), 64–85. https://doi.org/10.18559/ebr.2019.2.4

Rachwał, T. & Dominiak, J. (2022). Changes in industry and services sectors in Poland during the COVID-19 pandemic. *Quaestiones Geographicae*, *41* (4), 41–56. https://doi.org/10.14746/quageo-2022-0040

Radulescu, C. V., Ladaru, G-R., Burlacu, S., Constantin, F., Ioanăș, C. & Petre, I. L. (2020). Impact of the COVID-19 Pandemic on the Romanian Labor Market. *Sustainability*, *13* (1), 271. https://doi.org/10.3390/su13010271

Rakhmatullina, A. R., Sosunova, L. A. & Zubtsova, Y. (2022). Digital Development and Formation of Logistics Systems in Construction in Samara Region. In S.I. Ashmarina, V.V. Mantulenko (Eds), *Digital Technologies in the New Socio-Economic Reality. ISCDTE 2021* (pp. 321–328). Cham: Springer. https://doi.org/10.1007/978-3-030-83175-2_41

Rothan, H. A. & Byrareddy, S. N. (2020). The epidemiology and pathogenesis of coronavirus disease (COVID-19) outbreak. *Journal of Autoimmunity*, *109*, 102433. https://doi.org/10.1016/j.jaut.2020.102433

Said, H. & El-Rayes, K. (2014). Automated multi-objective construction logistics optimization system. *Automation in Construction*, *43*, 110–122. https://doi.org/10.1016/j.autcon.2014.03.017

Sjekavica Klepo, M., Damić, M., Milaković, G., Radaković, S. & Peroš, P. (2025). Overview of national construction market in the Republic of Croatia. *Journal of the Croatian Association of Civil Engineers*, *76* (12), 1115–1128. https://doi.org/10.14256/JCE.3523.2022

Sochacki, M. (2024). *Polish construction industry leads growth in Europe in years of turbulence caused by COVID-19 pandemic and war in Ukraine*. Retrieved from: https://www.euroconstruct.org/news/2024_01_pl/ [accessed: 14.08.2025].

Sumalla-Cano, S., Forbes-Hernández, T., Aparicio-Obregón, S., Crespo, J., Eléxpuru-Zabaleta, M., Gracia-Villar, M., Giampieri, F. & Elío, I. (2022). Changes in the Lifestyle of the Spanish University Population during Confinement for COVID-19. *International Journal of Environmental Research and Public Health*, *19* (4). https://doi.org/10.3390/ijerph19042210

Statistics Belgium [Statbel]. (2025). *Building permits* (archive). Retrieved from: https://statbel.fgov.be/en/search?search_api_fulltext_block=Building+permits%3A [accessed: 29.07.2025].

Tymoshchuk, Y., Suray, I., Hrebeniuk, H., Zadoia, V. & Selishchev, S. (2025). Government strategy for enhancing the infrastructure of international freight railway corridors: Economic and strategic considerations. *Edelweiss Applied Science and Technology*, *9* (2), 374–383. https://doi.org/10.55214/25768484.v9i2.4491

Vasiliev, A. & Bruskin, S. (2022). Key Indicators, Innovations, Trends, and Main Factors Influencing Transformation of the Building Construction Industry in Russia. In E. Zaramenskikh, A. Fedorova (Eds), *Digitalization of Society, Economics and Management* (pp. 15–28). Cham: Springer. https://doi.org/10.1007/978-3-030-94252-6_2

Vidalakis, C., Tookey, J. E. & Sommerville, J. (2011). Logistics simulation modelling across construction supply chains. *Construction Innovation*, *11* (2), 212–228. https://doi.org/10.1108/14714171111124176

Wieczorek, K. & Dzięcioł, J. (2025). Analysis of the impact of the global crisis in 2021–2024 on the development time of multifamily blocks. *Acta Scientiarum Polonorum. Architectura*, *24*, 28–48. https://doi.org/10.22630/ASPA.2025.24.3

World Bank [WB]. (2025). *World Development Indicators*. Retrieved from: https://databank.worldbank.org/source/world-development-indicators [accessed: 27.07.2025].

World Health Organization. Regional Office for the Eastern Mediterranean [WHO EMRO]. (2020). *Nutrition for adults during COVID-19*. Campaigns on NCDs. Retrieved from: https://www.emro.who.int/noncommunicable-diseases/campaigns/nutrition-for-adults-during-covid-19.html [accessed: 10.10.2025].

Zhou, C., Zhu, B., Halff, A., Davis, S. J., Liu, Z., Bowring, S., Arous, S. B. & Ciais, P. (2025). Europe's adaptation to the energy crisis: reshaped gas supply–transmission–consumption structures and driving factors from 2022 to 2024. *Earth System Science Data*, *17* (7), 3431–3446. https://doi.org/10.5194/essd-17-3431-2025

ANALIZA PORÓWNAWCZA LICZBY WYDANYCH POZWOLEŃ NA BUDOWĘ W POLSCE I WYBRANYCH KRAJACH EUROPEJSKICH W LATACH 2019–2024 W KONTEKŚCIE UWARUNKOWAŃ GOSPODARCZYCH

STRESZCZENIE

Celem artykułu jest porównanie liczby wydanych pozwoleń na budowę w Polsce i czterech krajach europejskich w latach 2019–2024, przy czym kryterium wyboru kraju był poziom PKB per capita w roku referencyjnym 2019. Postawiono hipotezę, że kryzysy globalne – pandemia COVID-19 i wojna w Ukrainie – istotnie wpłynęły na aktywność inwestycyjną w sektorze budowlanym, zwłaszcza w krajach o niższym poziomie rozwoju gospodarczego. Analiza wykazała, że w Polsce liczba pozwoleń w regionie centralnym spadła z 49 632 w 2019 r. do 42 271 w 2024 r. W krajach o niższym poziomie PKB, takich jak Chorwacja i Rumunia (odpowiednio 13 898,49 i 11 601,89 euro per capita w 2019 r.), zaobserwowano większe wahania aktywności budowlanej, przy czym Rumunia odnotowała wzrost liczby pozwoleń na obiekty niemieszkalne do 4 033 925 w 2023 r. Zależność odporności sektora budowlanego od kryzysów gospodarczych potwierdzono empirycznie i w toku badań okazało się, że istnieje potrzeba ujednolicenia raportowania danych w krajach UE.

Słowa kluczowe: pozwolenia na budowę, kryzys globalny, produkt krajowy brutto, PKB, gospodarka kraju, plac budowy, cykl budowlany

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REVIEW PAPER

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ADVANCES IN STRUCTURAL ENGINEERING THROUGH ARTIFICIAL INTELLIGENCE: METHODS, CHALLENGES AND OPPORTUNITIES

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ABSTRACT

This paper reviews recent advances in applying artificial intelligence (AI) in structural engineering, with a particular focus on methods, challenges, and opportunities. It examines how machine learning, deep learning, and evolutionary algorithms are transforming traditional design, analysis, and maintenance processes. The integration of AI with building information modelling (BIM), digital twins, and sensor-based monitoring systems is creating a more data-driven engineering environment. However, widespread adoption remains limited by issues such as data quality, model transparency, and a lack of validation frameworks. The study highlights the need for explainable models, ethical oversight, and standardised data practices to ensure the safe and reliable use of AI in structural applications.

Keywords: artificial intelligence, machine learning, deep learning, structural engineering, design optimisation, structural health monitoring

INTRODUCTION

Structural engineering has long relied on analytical models, empirical knowledge, and numerical simulations to design, analyse, and maintain safe and efficient structures. In recent years, the increasing complexity of structural systems and the scale of modern projects have highlighted the need for more advanced analytical and data-driven approaches beyond traditional engineering methods (Varshney, Pandey, Pandey & Singh, 2025). In this context, AI has emerged as a promising tool to help engineers make more accurate predictions, optimise designs, and automate repetitive or computationally demanding tasks (Aziz et al., 2025).

Techniques (Fig. 1) such as machine learning (ML), deep learning (DL), and evolutionary algorithms are now used across a wide range of structural engineering applications. They support tasks such as predicting structural performance under different loading conditions, detecting damage or deterioration in existing structures, optimising material use, and assisting in real-time monitoring and decision-making (Aziz et al., 2025; Bahadori-Jahromi et al., 2025). The growing integration of AI with BIM, digital twins, and sensor-based monitoring systems is further transforming the discipline into a data-driven and adaptive field (Deng, Menassa & Kamat, 2021; Azanaw, 2024).

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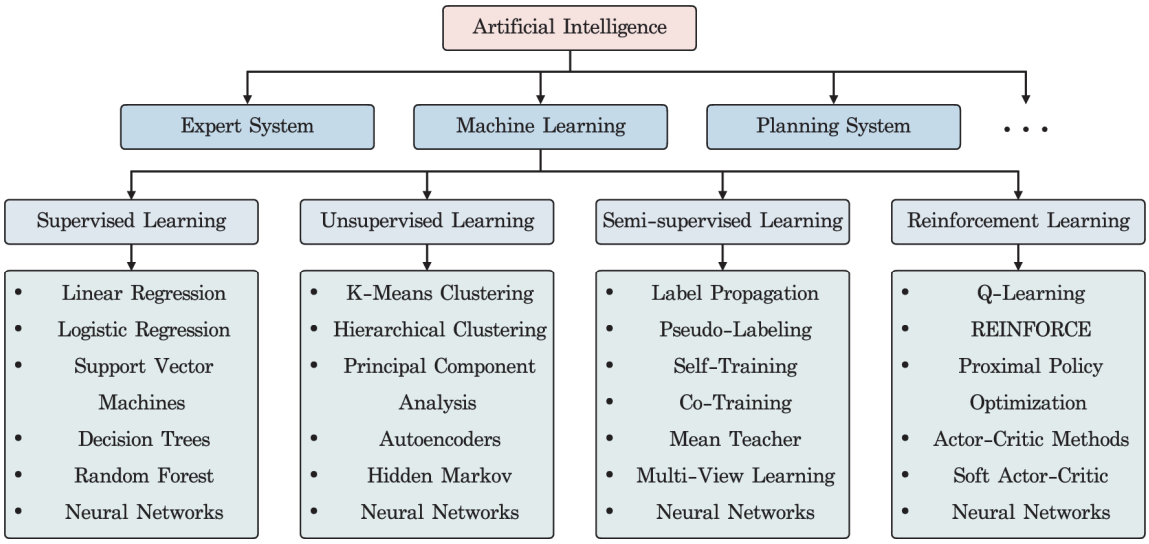


Fig. 1. Artificial intelligence and machine learning

Source: Ao, Li and Duan (2025).

The advantages of AI in structural engineering are significant. ML models can capture complex, nonlinear relationships within structural data, offering more precise and adaptable solutions than conventional analytical methods (Bahadori-Jahromi et al., 2025). DL, in particular, has proven effective in handling large datasets from sensors, images, and simulations, enabling accurate detection of structural anomalies and early warnings of potential failures (Luleci, Catbas & Avci, 2023). In parallel, optimisation algorithms inspired by natural processes, such as genetic algorithms and swarm intelligence, are helping to generate innovative structural designs that balance performance, cost, and sustainability (He, Wang & Zhang, 2025).

Despite these advancements, several challenges limit the widespread adoption of AI in structural engineering. These include limited access to high-quality labelled data, difficulties in interpreting AI models (the so-called "black box" problem), and the absence of standard frameworks for model validation and integration with existing engineering tools (Hassija et al., 2024; Bahadori-Jahromi et al., 2025). Moreover, while AI can improve both efficiency and accuracy, its outputs must always be reviewed critically by qualified engineers to ensure safety and compliance with design codes (Plevris & Hosamo, 2025).

This review provides an overview of current AI applications in structural engineering, summarising the main methods, benefits, and limitations identified in recent studies (Fig. 2). It categorises the literature into thematic areas, including design optimisation, structural analysis, material modelling, damage detection, and health monitoring, as well as discussing how AI contributes to each. The paper concludes with a discussion of future research directions, highlighting the potential of integrating AI with digital twins and physics--informed learning to reshape the future of structural engineering.

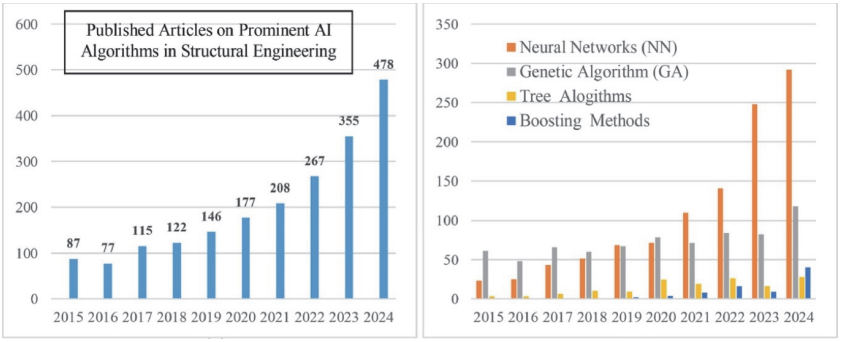


Fig. 2. Published article trends in structural engineering (Scopus-sourced, 2015–2024): (a) overall use of prominent artificial intelligence algorithms, (b) categorised by specific methods (NN, GA, tree-based, and boosting algorithms)

Source: Aziz et al. (2025).

This review adds value by providing a synthesis of AI applications across the full structural engineering lifecycle (design optimisation, material behaviour prediction, and structural health monitoring), where most existing reviews focus on only one area. It also integrates recent advances from 2023–2025, including generative models, physics-informed features, and explainable AI, offering an updated and cross-disciplinary perspective. The review is guided by three questions:

1. How are AI methods currently used across design, material performance and monitoring in structural engineering?
2. What data types and modelling approaches dominate these applications?
3. What limitations and practical barriers still restrict the wider adoption of AI in structural engineering?

METHODOLOGY

This paper is based on a structured narrative review of recent research on AI applications in structural engineering. The literature search covered the years 2019–2025 and relied on academic sources accessed through institutional subscriptions and open-access platforms, without relying on any single database. The review was guided by keyword groups such as: AI in structural engineering, machine learning for concrete, structural form finding, digital twins, structural health monitoring, generative materials design, steel additive manufacturing, computer vision construction safety, and Explainable Artificial Intelligence (XAI) for engineering.

The inclusion criteria were: (1) peer-reviewed or authoritative publications, (2) direct relevance to structural engineering or material behaviour, (3) clear use of AI/ML/DL methods, and (4) sufficient methodological detail. The exclusion criteria removed articles unrelated to structures, with weak methodological transparency, or offering no new insight.

APPLICATIONS OF AI IN STRUCTURAL ENGINEERING

Design optimisation and structural form finding

ML in structural design addresses the optimisation of structural form and element layout to reduce material use, costs, and construction clashes while preserving required safety and functionality. The workflows usually rely on BIM models, geometric parameters, material data, load cases, Finite Elements Method outputs and, in reinforcement design, graph-based representations of rebar arrangements. The main AI approaches include genetic algorithms that explore extensive design spaces, as well as graph neural networks combined with evolutionary optimisation for a clash-free reinforcement layout, as shown, for example, by Sherif, Nassar, Hosny, Safar & Abotaleb (2022) and Li, Liu, Wong, Gan & Cheng (2023). These methods are already mature at the research and pilot-application level, particularly in settings with strong BIM integration. Their limitations are high computational effort, inconsistent data standards between tools, limited automation for very complex reinforcement scenarios, and the continued need for engineers to verify results before implementation.

Material behaviour and performance prediction

Generative and predictive AI address a wide set of engineering problems in structural materials science, from discovering new material compositions to forecasting the mechanical behaviour of concrete, steel, and wood. In material discovery, the core challenge is navigating an enormous chemical design space to identify compounds with desired mechanical and thermal properties. Typical data include crystal structures, chemical compositions, thermodynamic parameters, and large simulation-derived datasets. Generative models predict formation energy, structural stability, and synthesizability, which shortens the discovery cycle, as shown by Merchant et al. (2023), Cheetham and Seshadri (2024), Ma et al. (2024), and Han and Su (2025). Ensemble learning and DL methods dominate in predicting concrete compressive strength, using datasets that combine mix proportions, curing conditions, and laboratory test results. CNNs and ANNs consistently outperform traditional regression-based approaches (Das et al., 2024; Hosseinzadeh, Samadvand, Hosseinzadeh, Mousavi & Dehestani, 2024; Muthurathinamm Alruwais, Al Mazroa & Alkharashi, 2024; Luo et al., 2025). For steel structures, the engineering problem concerns predicting mechanical performance under varying manufacturing or additive manufacturing parameters. ML models rely on data describing heat input, fibre content, microstructure, or printing conditions. CNN-based systems for steel fibre-reinforced concrete achieve higher accuracy than classical methods, while ML in metal additive manufacturing enables real-time tuning of process parameters (Gong, Zeng, Groeneveld-Meijer & Manogharan, 2022; Pakzad, Roshan & Ghalehnovi, 2023; Akbari, Zamani & Mostafaei, 2024). Similar principles apply to buckling-restrained braced frames, where ML uses physics-informed features such as eccentric loading ratios and material properties to simulate seismic response (Asgarkhani et al., 2024; Mohamed et al., 2024).

Wood structures pose a different engineering problem, which is strong natural variability. Models use image data showing fibre patterns, growth defects, or grain structure, supplemented with sensor readings on moisture and environmental conditions. DL and transfer learning methods allow automatic quality assessment and property prediction with limited datasets (Lukovic et al., 2024; Al-Mattarneh et al., 2025; González-Palacio, García-Giraldo & González-Palacio, 2025; Quinteros-Navarro, Quinteros, Muñoz, Ramirez & Ramirez, 2025). Neural networks combined with sensor data provide non-destructive, continuous monitoring of moisture and strength (Al-Mattarneh et al., 2025; Quinteros-Navarro et al., 2025). Across all these domains, explainable AI is gaining importance. Tools such as SHAP (SHapley Additive exPlanations) and LIME help identify which variables drive predictions, improving model transparency and trust. In concrete applications, XAI consistently highlights the influence of the water-to-cement ratio, cement content, and curing time, quantifying their contribution to predicted strength (Luo et al., 2025; Zhang et al., 2023; Zhang et al., 2024; Zheng et al., 2025).

Generative models for material discovery are rapidly advancing but still rely on extensive simulation data and expert validation. Predictive models for concrete, steel, and wood are more widely tested, yet full deployment depends on reliable datasets and integration with existing engineering workflows. Key limitations include data scarcity for specialised materials, a lack of standardised datasets, high computational costs for generative modelling, and the need for careful human verification before results are used in design or manufacturing.

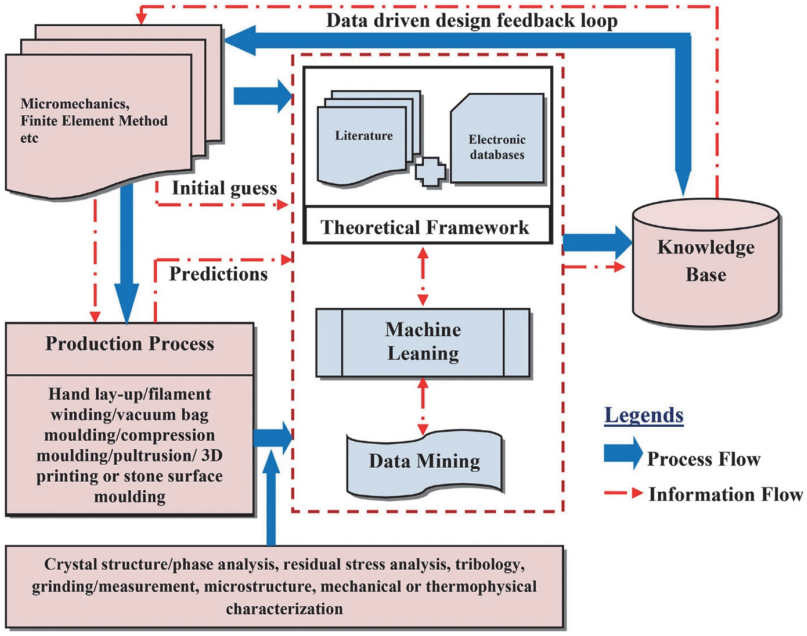


Fig. 3. Data-driven design of composite material process

Source: Okafor et al. (2023).

Damage detection and structural health monitoring

AI and Internet of Things (IoT) address a clear engineering problem: the need for continuous, accurate and non-destructive monitoring of structural performance throughout a building's life cycle. Typical data include sensor readings on temperature, humidity, vibration, strain, displacement, load response, and material degradation, complemented by BIM information and time-stamped environmental records. DL models now support ultrasonic methods for concrete, allowing real-time strength assessment without damaging the structure, as shown by Gan et al. (2025). When these data streams are combined with digital twins, engineers gain a dynamic representation of the structure. Integrating BIM models, sensor inputs, and predictive algorithms enables continuous tracking of performance and early detection of degradation trends, which supports proactive maintenance planning (Deng et al., 2021; Azanaw, 2024). AI also improves safety on construction sites: computer vision systems analyse standard camera feeds to identify unsafe behaviours or hazardous situations and generate immediate alerts, reducing accidents and downtime (Badeka et al., 2025). The maturity level of these technologies ranges from well-developed research prototypes to early industrial adoption, especially in organisations that already use BIM and sensor networks. Key limitations are inconsistent data quality from on-site sensors, limited interpretability of complex DL models, and a lack of unified validation standards that

would allow engineers to trust predictions in critical decisions. Despite these challenges, AI offers substantial potential to enhance monitoring, maintenance, and structural resilience, while gradually shifting the engineer's role toward more analytical, supervisory and decision-oriented work.

Table 1. Methods, challenges and opportunities of AI in Structural Engineering

Category	Description	Example
	Methods	
Machine learning (ML), deep learning (DL)	Neural networks, support vector machines, and deep architectures are used to predict structural behaviour, damage evolution, or material properties.	Used in structural health monitoring and predictive maintenance (Flah, Nunez, Ben Chaabene & Nehdi, 2021; Spencer, Sim, Kim & Yoon, 2025).
Computer vision and image processing	Artificial intelligence-based crack, corrosion, and deformation detection using drone or camera imagery.	Automated infrastructure inspection (Tyvoniuk, Trach & Trach, 2025).
Surrogate modelling	Simplified models trained on simulation or experimental data to accelerate analysis.	Applied in topology optimisation and meta-modelling (Ao et al., 2025).
Artificial intelligence-based multi-objective optimisation	Coupling ML/DL with heuristic algorithms (e.g., particle swarm optimisation, genetic algorithms) for design optimisation under constraints.	Generative structural design systems (Ao et al., 2025).
Integration with digital twins	AI supports predictive modelling and real-time analysis in digital replicas of structures.	Enables real-time performance assessment, degradation prediction, and adaptive control in smart infrastructure systems (Azanaw, 2024; Spencer et al., 2025).
	Challenges	
Data quality and availability	Structural datasets are often incomplete, small-scale, or inconsistent, which limits model accuracy.	Need for standardised, domain-specific datasets (Bao et al., 2025; Mengesha, 2025).
Model interpretability and trust	AI, especially DL, operates as a "black box," which reduces engineers' confidence in its results.	Lack of explainable AI tools for engineering (Plevris & Hosamo, 2025; Salman, Al-Shaikhli, Ali Abbas, Ahmad & Kudus, 2025).
Reliability in real-world applications	Lab-trained models may fail in real structures due to varying conditions and noise.	Need for robust validation of field data (Zaker Esteghamati, Bean, Burton & Naser, 2025).
Integration with codes and practice (Xie, Mei & Chui, 2025)	Difficulties incorporating AI into engineering workflows and meeting design standards.	Resistance to non-traditional computational methods.
Ethical and safety considerations	AI-driven decisions affect public safety, raising questions of accountability and bias.	Ethical frameworks and human oversight required (Plevris & Hosamo, 2025).
	Opportunities	
Faster and more efficient structural design	AI enables rapid exploration of multiple design scenarios and accelerates optimisation.	Reduced design time and computational cost (Ao et al., 2025; He et al., 2025).
Early fault detection and predictive maintenance	AI predicts when structures need inspection or repair, improving safety and reducing costs.	Bridge and infrastructure monitoring (Bao et al., 2025; Spencer et al., 2025).
Material and structural optimisation	AI aids in designing lightweight, efficient structures and optimising material use.	Topology and geometry optimisation (Xie et al., 2025).
Enhanced resilience and risk management	AI helps simulate and mitigate extreme or uncertain loading scenarios.	Seismic and wind resilience analysis (Harirchian et al., 2020; Zhang et al., 2023).
Evolving role of engineers	AI automates routine analysis, allowing engineers to focus on creative and critical aspects.	Requires education and adaptation to AI-driven workflows (Plevris & Hosamo, 2025).

Source: own work.

CHALLENGES AND LIMITATIONS

Data quality remains one of the most critical barriers to applying AI in structural engineering. Building reliable AI models requires access to large, diverse, and high-quality datasets, yet the field continues to struggle with small sample sizes, inconsistent data collection, and a lack of standardised formats. Traditional datasets often capture only narrow case studies or laboratory conditions, limiting their usefulness for training robust surrogate models. The problem is especially acute for rare or extreme events such as earthquakes or structural failures, where historical data are scarce and incomplete (Hong, Kwon, Shin, Park & Kang, 2024; Fei, Lu, Liao & Guan, 2025; Salman et al., 2025; Varshney et al., 2025; Wala, 2025). Poor data quality can introduce bias, reduce model reliability, and lead to inaccurate predictions. Missing values, unrepresentative samples, or hidden data errors may remain undetected yet significantly increase the risk of failure in future applications. In safety-critical domains like structural engineering, even minor deficiencies in data quality can have serious or catastrophic consequences (Foidl, Felderer & Ramler, 2022; Parmar, Gupta, Chouhan & Saran, 2023; Gómez Plaza et al., 2025).

The "black-box" nature of many AI models presents another major challenge. Deep neural networks, though powerful, often lack transparency, making it difficult for engineers to understand or justify their decisions in design and safety assessments. This lack of interpretability conflicts with the core principles of professional accountability and with regulatory requirements demanding traceable, explainable design reasoning (Felderer & Ramler, 2021; Porter, Habli, McDermid & Kaas, 2024; Salman et al., 2025; Wala, 2025).

XAI has emerged as a promising response to this problem, offering methods to uncover how complex models reach their conclusions. However, implementing effective explainability in practice remains difficult, particularly for DL architectures where high accuracy often comes at the cost of interpretability. Striking the right balance between performance and transparency is essential, especially in contexts involving cultural heritage structures, public safety, or compliance with design codes (Mirzaei, Mao, Al-Nima & Woo, 2023; Geyer, Singh & Chen, 2024; Marey et al., 2024).

Another limitation lies in the computational demands of AI. Training and deploying advanced models require high-performance GPUs and substantial energy resources. While major research institutions and large engineering firms can afford such infrastructure, smaller practices and organisations in developing regions often face significant barriers to entry. GPU-accelerated computing has become indispensable for modern AI applications, but its environmental footprint and cost raise sustainability concerns (Fischer et al., 2020; Canakci et al., 2025). The issue extends beyond training: real-time structural monitoring systems must process continuous sensor data, which further increases computational load. Although edge computing offers partial relief by distributing computation across devices, it introduces new technical and operational complexities (Asadi et al., 2018; Mishra, Gangisetti & Khazanchi, 2023).

AI models in structural engineering often face difficulties when applied beyond the conditions on which they were trained. The field encompasses an extraordinary range of building types, materials, environmental contexts, and loading scenarios, which makes it challenging to create models that generalise well across all cases. Overfitting, under specification, and biases in training data remain common issues, while the omission of key variables can lead to misleading or overly confident predictions (Felderer & Ramler, 2021; Salman et al., 2025; Zaker Esteghamati et al., 2025).

Cross-validation techniques can help evaluate model robustness, but a deeper problem persists: structural engineering often involves rare, high-impact events such as extreme loading, material fatigue, or seismic failure, for which historical data are inherently scarce. In such cases, uncertainty quantification becomes essential to convey the confidence and limitations of model predictions. However, many AI frameworks still struggle to produce reliable measures of uncertainty, leaving engineers without a clear understanding of how much trust to place in automated outputs (Felderer & Ramler, 2021; Wang et al., 2022; Dalrymple et al., 2024).

Strengths	Weaknesses
– Enhanced efficiency in design and analysis as AI automates repetitive tasks, accelerates simulations, and supports real-time optimisation. – Improved accuracy and early fault detection as AI models outperform traditional statistical approaches in detecting cracks, anomalies, and material degradation. – Integration with Digital Twin systems enables predictive maintenance, continuous monitoring, and performance forecasting. – Capability to process multimodal data (images, vibration signals, environmental parameters) for holistic analysis.	– Limited availability and quality of structural datasets; many are proprietary or too small for robust model training. – Low interpretability of deep models ("black box" nature) reduces trust and transparency in safety-critical engineering contexts. – Integration challenges with existing BIM workflows, design codes, and verification procedures. – High initial cost and expertise barrier as implementation requires interdisciplinary skills (AI, structural mechanics, data engineering).
Opportunities	**Threats**
– Adoption of XAI and hybrid physics-informed models could make AI results more transparent and acceptable for regulatory frameworks. – Integration with sustainability and resilience goals, as AI-driven optimisation can reduce material use and energy consumption in design. – Development of open structural data platforms could accelerate collaboration and innovation in the field. – Growth of generative design and AI-assisted decision-making in early conceptual stages allows exploration of novel, efficient structures.	– Regulatory and legal uncertainty, lack of standards defining AI validation, liability, and model approval in engineering. – Overreliance on AI without sufficient engineering validation may lead to unsafe or non-compliant designs. – Cybersecurity risks in AI-driven monitoring systems, especially in critical infrastructure. – Potential job displacement or skill mismatch; engineers must adapt to data-centric workflows.

Fig. 4. SWOT analysis: Structural engineering through artificial intelligence

Source: own work.

Finally, the integration of AI introduces complex ethical and professional questions regarding accountability and oversight. When an AI-generated design or recommendation contributes to a structural failure, responsibility becomes blurred: does it rest with the developer of the algorithm, the engineer applying it, or the institution endorsing its use? This ambiguity is especially problematic given the opaque, "black-box" nature of many AI systems, underscoring the need for clear governance frameworks and continued human supervision in all safety-critical engineering decisions (Ryan, Porter, Al-Qaddoumi, McDermid & Habli, 2023; Clymer, Gabrieli, Krueger & Larsen, 2024; V Khadake, 2024).

CONCLUSIONS

As presented in Figure 4, AI is transforming structural engineering by introducing data-driven methods that enhance design, analysis, and monitoring. Techniques such as ML, DL, and evolutionary algorithms make it possible to optimise structures more efficiently, predict material behaviour with greater accuracy, and assess performance in real time. When combined with BIM, digital twins, and IoT technologies, AI enables continuous data exchange throughout the entire lifecycle of a structure, supporting predictive maintenance and more informed, sustainable decision-making.

Despite these advances, the widespread use of AI in structural engineering is still limited by several challenges, including data scarcity, limited model interpretability, the absence of consistent validation frameworks, and difficulties integrating AI with established design codes and professional practice. Maintaining

transparency, ethical oversight, and human control remains vital to ensure safety and accountability in all AI-assisted processes.

Future work should aim to develop explainable and physics-informed AI models, promote open and standardised data infrastructures, and establish clear regulatory frameworks for their use. These efforts will allow AI to serve as a powerful complement (not a replacement) to engineering expertise, helping to build a safer, more efficient, and sustainable built environment.

Authors' contributions

Conceptualisation: M.K.; methodology: M.K.; validation: M.K.; formal analysis: M.K.; investigation: M.K.; resources: M.K.; data curation: M.K.; writing – original draft preparation: M.K.; writing – review and editing: M.K.; visualisation: M.K.; supervision: M.K. and R.D.; project administration: M.K.; funding acquisition: M.K.

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REFERENCES

Akbari, P., Zamani, M. & Mostafaei, A. (2024). Machine learning prediction of mechanical properties in metal additive manufacturing. *Additive Manufacturing*, *19*, 104320. https://doi.org/10.1016/j.addma.2024.104320

Al-Mattarneh, H., Ismail, R., Trrad, I., Nimer, H., Khodier, M., Jaradat, Y., Malkawi, A. B. & Mohammed, B. S. (2025). Using artificial neural networks and electromagnetic capacitive NDT sensors for wood engineering application. *HBRC Journal*, *21* (1), 211–233. https://doi.org/10.1080/16874048.2025.2471122

Ao, Y., Li, S. & Duan, H. (2025). Artificial Intelligence-Aided Design (AIAD) for Structures and Engineering: A State-of-the-Art Review and Future Perspectives. *Archives of Computational Methods in Engineering*, *32* (7), 4197–4224. https://doi.org/10.1007/s11831-025-10264-1

Asadi, K., Ramshankar, H., Pullagurla, H., Bhandare, A., Shanbhag, S., Mehta, P., Kundu, S., Han, K., Lobaton, E. & Wu, T. (2018, July 22). Building an Integrated Mobile Robotic System for Real-Time Applications in Construction. *2018 In Proceedings of the 35th ISARC, Berlin, Germany* (pp. 453–461). The International Association for Automation and Robotics in Construction. https://doi.org/10.22260/ISARC2018/0063

Asgarkhani, N., Kazemi, F., Jakubczyk-Gałczyńska, A., Mohebi, B., & Jankowski, R. (2024). Seismic response and performance prediction of steel buckling-restrained braced frames using machine-learning methods. *Engineering Applications of Artificial Intelligence*, *128*, 107388. https://doi.org/10.1016/j.engappai.2023.107388

Azanaw, Mr. G. M. (2024). Revolutionizing Structural Engineering: A Review of Digital Twins, BIM, and AI Applications. *Indian Journal of Structure Engineering*, *4* (2), 1–8. https://doi.org/10.54105/ijse.B1321.04021124

Aziz, Md. T., Osabel, D. M., Kim, Y., Kim, S., Bae, J. & Tsavdaridis, K. D. (2025). State-of-the-art artificial intelligence techniques in structural engineering: A review of applications and prospects. *Results in Engineering*, *28*, 107882. https://doi.org/10.1016/j.rineng.2025.107882

Badeka, E., Muchla, A., Koulalis, I., Ioannidis, K., Dymarski, P. & Vrochidis, S. (2025). Ladder Walking Detection via Action Recognition for Enhancing Worker Safety in Construction. In *2025 IEEE International Workshop on Metrology for Living Environment (MetroLivEnv)* (pp. 345–349). IEEE International. https://doi.org/10.1109/MetroLivEnv64961.2025.11107036

Bahadori-Jahromi, A., Room, S., Paknahad, C., Altekreeti, M., Tariq, Z. & Tahayori, H. (2025). The Role of Artificial Intelligence and Machine Learning in Advancing Civil Engineering: A Comprehensive Review. *Applied Sciences*, *15* (19), 10499. https://doi.org/10.3390/app151910499

Bao, Y., Sun, H., Xu, Y., Guan, X., Pan, Q. & Liu, D. (2025). Recent advances in structural health diagnosis: a machine learning perspective. *Advances in Bridge Engineering*, *6* (1), 7. https://doi.org/10.1186/s43251-024-00155-z

Canakci, B., Liu, J., Wu, X., Cheriere, N., Costa, P., Legtchenko, S., Narayanan, D. & Rowstron, A. (2025). Good things come in small packages: Should we build AI clusters with Lite-GPUs? In *Proceedings of the Workshop on Hot Topics in Operating Systems* (pp. 127–135). New York: Association for Computing Machinery. https://doi.org/10.1145/3713082.3730390

Cheetham, A. K. & Seshadri, R. (2024). Artificial Intelligence Driving Materials Discovery? Perspective on the Article: Scaling Deep Learning for Materials Discovery. *Chemistry of Materials*, *36* (8), 3490–3495. https://doi.org/10.1021/acs.chemmater.4c00643

Clymer, J., Gabrieli, N., Krueger, D. & Larsen, T. (2024). *Safety Cases: How to Justify the Safety of Advanced AI Systems*. *arXiv:2403.10462*. https://doi.org/10.48550/arXiv.2403.10462

Dalrymple, D., Skalse, J., Bengio, Y., Russell, S., Tegmark, M., Seshia, S., Omohundro, S., Szegedy, C., Goldhaber, B., Ammann, N., Abate, A., Halpern, J., Barrett, C., Zhao, D., Zhi-Xuan, T., Wing, J. & Tenenbaum, J. (2024). Towards Guaranteed Safe AI: A Framework for Ensuring Robust and Reliable AI Systems. *arXiv:2405.06624*. https://doi.org/10.48550/arXiv.2405.06624

Das, P., Kashem, A., Islam, M., Ahmed, A., Haque, M. A. & Khan, M. (2024). Alkali-activated binder concrete strength prediction using hybrid-deep learning along with shapely additive explanations and uncertainty analysis. *Construction and Building Materials*, *435*, 136711. https://doi.org/10.1016/j.conbuildmat.2024.136711

Deng, M., Menassa, C. C. & Kamat, V. R. (2021). From BIM to digital twins: a systematic review of the evolution of intelligent building representations in the AEC-FM industry. *Journal of Information Technology in Construction*, *26*, 58–83. https://doi.org/10.36680/j.itcon.2021.005

Fei, Y., Lu, X., Liao, W. & Guan, H. (2025). Data enhancement for generative AI design of shear wall structures incorporating structural optimization and diffusion models. *Advances in Structural Engineering*. https://doi.org/10.1177/13694332251353614

Felderer, M. & Ramler, R. (2021). *Quality Assurance for AI-based Systems: Overview and Challenges*. https://doi.org/10.1007/978-3-030-65854-0_3

Fischer, L., Ehrlinger, L., Geist, V., Ramler, R., Sobiezky, F., Zellinger, W., Brunner, D., Kumar, M. & Moser, B. (2020). AI System Engineering – Key Challenges and Lessons Learned. *Machine Learning and Knowledge Extraction*, *3* (1), 56–83. https://doi.org/10.3390/make3010004

Flah, M., Nunez, I., Ben Chaabene, W. & Nehdi, M. L. (2021). Machine Learning Algorithms in Civil Structural Health Monitoring: A Systematic Review. *Archives of Computational Methods in Engineering*, *28* (4), 2621–2643. https://doi.org/10.1007/s11831-020-09471-9

Foidl, H., Felderer, M. & Ramler, R. (2022). *Data Smells: Categories, Causes and Consequences, and Detection of Suspicious Data in AI-based Systems*. *arXiv:2203.10384*. https://doi.org/10.48550/arXiv.2203.1038

Gan, X., Wang, W., Jiang, C., Ye, L., Chen, F., Zhou, T. & Zhao, Y. (2025). Ultrasonic detection and deep learning for high-precision concrete strength prediction. *Journal of Building Engineering*, *104*, 112372. https://doi.org/10.1016/j.jobe.2025.112372

Geyer, P., Singh, M. M. & Chen, X. (2024). Explainable AI for engineering design: A unified approach of systems engineering and component-based deep learning demonstrated by energy-efficient building design. *Advanced Engineering Informatics*, *62*, 102843. https://doi.org/10.1016/j.aei.2024.102843

Gong, X., Zeng, D., Groeneveld-Meijer, W. & Manogharan, G. (2022). Additive manufacturing: A machine learning model of process-structure-property linkages for machining behavior of Ti-6Al-4V. *Materials Science in Additive Manufacturing*, *1* (1), 6. https://doi.org/10.18063/msam.v1i1.6

González-Palacio, M., García-Giraldo, J. M. & González-Palacio, L. (2025). Integrating AI and sustainable materials: machine learning approaches to wood structural behavior. *Agronomy Research*, *23*, 2025. https://doi.org/10.15159/AR.25.073

Gómez Plaza, M., Granados Cañete, F. J., López Yajamin, E. X., Díaz Martín, D., Olalla Caballero, B. & Palma Bautista, A. M. (2025). Enhancing AI applications for European public bodies: A data quality-centric approach. *International Journal of Engineering Business Management*, *17*. https://doi.org/10.1177/18479790251367820

Han, N. & Su, B.-L. (2025). AI-driven material discovery for energy, catalysis and sustainability. *National Science Review*, *12* (5). https://doi.org/10.1093/nsr/nwaf110

Harirchian, E., Kumari, V., Jadhav, K., Raj Das, R., Rasulzade, S. & Lahmer, T. (2020). A Machine Learning Framework for Assessing Seismic Hazard Safety of Reinforced Concrete Buildings. *Applied Sciences*, *10* (20), 7153. https://doi.org/10.3390/app10207153

Hassija, V., Chamola, V., Mahapatra, A., Singal, A., Goel, D., Huang, K., Scardapane, S., Spinelli, I., Mahmud, M. & Hussain, A. (2024). Interpreting Black-Box Models: A Review on Explainable Artificial Intelligence. *Cognitive Computation*, *16* (1), 45–74. https://doi.org/10.1007/s12559-023-10179-8

He, Z., Wang, Y-H. & Zhang, J. (2025). Generative AIBIM: An automatic and intelligent structural design pipeline integrating BIM and generative AI. *Information Fusion*, *114*, 102654. https://doi.org/10.1016/j.inffus.2024.102654

Hong, S., Kwon, Y., Shin, D., Park, J. & Kang, N. (2024). DeepJEB: 3D Deep Learning-based Synthetic Jet Engine Bracket Dataset. *arXiv:2406.09047*. https://doi.org/10.48550/arXiv.2406.09047

Hosseinzadeh, M., Samadvand, H., Hosseinzadeh, A., Mousavi, S. S. & Dehestani, M. (2024). Concrete strength and durability prediction through deep learning and artificial neural networks. *Frontiers of Structural and Civil Engineering*, *18* (10), 1540–1555. https://doi.org/10.1007/s11709-024-1124-9

Li, M., Liu, Y., Wong, B. C. L., Gan, V. J. L. & Cheng, J. C. P. (2023). Automated structural design optimization of steel reinforcement using graph neural network and exploratory genetic algorithms. *Automation in Construction*, *146*, 104677. https://doi.org/10.1016/j.autcon.2022.104677

Lukovic, M., Ciernik, L., Müller, G., Kluser, D., Pham, T., Burgert, I. & Schubert, M. (2024). Probing the complexity of wood with computer vision: from pixels to properties. *Journal of The Royal Society Interface*, *21* (213). https://doi.org/10.1098/rsif.2023.0492

Luleci, F., Catbas, F. N. & Avci, O. (2023). Generative adversarial networks for labeled acceleration data augmentation for structural damage detection. *Journal of Civil Structural Health Monitoring*, *13* (1), 181–198. https://doi.org/10.1007/s13349-022-00627-8

Luo, D., Wang, K., Wang, D., Sharma, A., Li, W. & Choi, I. H. (2025). Artificial intelligence in the design, optimization, and performance prediction of concrete materials: a comprehensive review. *Npj Materials Sustainability*, *3* (1), 14. https://doi.org/10.1038/s44296-025-00058-8

Ma, J., Cao, B., Dong, S., Tian, Y., Wang, M., Xiong, J. & Sun, S. (2024). MLMD: a programming-free AI platform to predict and design materials. *Npj Computational Materials*, *10* (1), 59. https://doi.org/10.1038/s41524-024-01243-4

Marey, A., Arjmand, P., Alerab, A. D. S., Eslami, M. J., Saad, A. M., Sanchez, N. & Umair, M. (2024). Explainability, transparency and black box challenges of AI in radiology: impact on patient care in cardiovascular radiology. *Egyptian Journal of Radiology and Nuclear Medicine*, *55* (1), 183. https://doi.org/10.1186/s43055-024-01356-2

Mengesha, G. (2025). *Integrating AI in Structural Health Monitoring (SHM): A Systematic Review on Advances, Challenges, and Future Directions*. https://doi.org/10.2139/ssrn.5004977

Merchant, A., Batzner, S., Schoenholz, S. S., Aykol, M., Cheon, G. & Cubuk, E. D. (2023). Scaling deep learning for materials discovery. *Nature*, *624* (7990), 80–85. https://doi.org/10.1038/s41586-023-06735-9

Mirzaei, S., Mao, H., Al-Nima, R. R. O. & Woo, W. L. (2023). Explainable AI Evaluation: A Top-Down Approach for Selecting Optimal Explanations for Black Box Models. *Information*, *15* (1), 4. https://doi.org/10.3390/info15010004

Mishra, A., Gangisetti, G. & Khazanchi, D. (2023). Integrating Edge-AI in Structural Health Monitoring domain. *arXiv:2304.03718*. https://doi.org/10.48550/arXiv.2304.03718

Mohamed, H. S., Qiong, T., Isleem, H. F., Tipu, R. K., Shahin, R. I., Yehia, S. A., Jangir, P., Arpita, & Khishe, M. (2024). Compressive behavior of elliptical concrete-filled steel tubular short columns using numerical investigation and machine learning techniques. *Scientific Reports*, *14* (1), 27007. https://doi.org/10.1038/s41598-024-77396-5

Muthurathinam, R. V., Alruwais, N., Al Mazroa, A. & Alkharashi, A. (2024). Optimizing concrete compressive strength prediction with a deep forest model: an advanced machine learning approach. *Matéria (Rio de Janeiro)*, *29* (4). https://doi.org/10.1590/1517-7076-rmat-2024-0569

Okafor, C. E., Iweriolor, S., Ani, O. I., Ahmad, S., Mehfuz, S., Ekwueme, G. O., Chukwumuanya, O. E., Abonyi, S. E., Ekengwu, I. E. & Chikelu, O. P. (2023). Advances in machine learning-aided design of reinforced polymer composite and hybrid material systems. *Hybrid Advances*, *2*, 100026. https://doi.org/10.1016/j.hybadv.2023.100026

Pakzad, S. S., Roshan, N. & Ghalehnovi, M. (2023). Comparison of various machine learning algorithms used for compressive strength prediction of steel fiber-reinforced concrete. *Scientific Reports*, *13* (1), 3646. https://doi.org/10.1038/s41598-023-30606-y

Parmar, D. S., Gupta, P., Chouhan, C. & Saran, H. K. (2023). Data-centric AI: Prioritizing Data Quality Over Model Complexity. *International Journal of Innovative Research in Computer and Communication Engineering*, *11* (07). https://doi.org/10.15680/IJIRCCE.2023.1107004

Plevris, V. & Hosamo, H. (2025). Responsible AI in structural engineering: a framework for ethical use. *Frontiers in Built Environment*, *11*. https://doi.org/10.3389/fbuil.2025.1612575

Porter, Z., Habli, I., McDermid, J. & Kaas, M. (2024). A principles-based ethics assurance argument pattern for AI and autonomous systems. *AI and Ethics*, *4* (2), 593–616. https://doi.org/10.1007/s43681-023-00297-2

Quinteros-Navarro, D., Quinteros, A., Muñoz, V., Ramirez, H. & Ramirez, W. (2025). Learning Model Based on Artificial Intelligence to Determine Wood Quality: A Systematic Review. *Ingénierie Des Systèmes d Information*, *30* (2), 427–436. https://doi.org/10.18280/isi.300214

Ryan, P., Porter, Z., Al-Qaddoumi, J., McDermid, J. & Habli, I. (2023). What's my role? Modelling responsibility for AI-based safety-critical systems. *arXiv:2401.09459*. https://doi.org/10.48550/arXiv.2401.09459

Salman, M. R., Al-Shaikhli, M., Ali Abbas, H., Ahmad, H. H. & Kudus, S. A. (2025). A critical review of deep learning applications, challenges, and future directions in structural engineering. *International Journal for Computational Civil and Structural Engineering*, *21* (1), 146–156. https://doi.org/10.22337/2587-9618-2025-21-1-146-156

Sherif, M., Nassar, K., Hosny, O., Safar, S. & Abotaleb, I. (2022). Automated BIM-based structural design and cost optimization model for reinforced concrete buildings. *Scientific Reports*, *12* (1), 21616. https://doi.org/10.1038/s41598-022-26146-6

Spencer, B. F., Sim, S.-H., Kim, R. E. & Yoon, H. (2025). Advances in artificial intelligence for structural health monitoring: A comprehensive review. *KSCE Journal of Civil Engineering*, *29* (3), 100203. https://doi.org/10.1016/j.kscej.2025.100203

Tyvoniuk, V., Trach, R. & Trach, Y. (2025). Integration of Probability Maps into Machine Learning Models for Enhanced Crack Segmentation in Concrete Bridges. *Applied Sciences*, *15* (6), 3201. https://doi.org/10.3390/app15063201

V Khadake. (2024). AI Ethics and Responsible AI Development: Navigating the Ethical Landscape of Artificial Intelligence. *International Journal of Scientific Research in Computer Science, Engineering and Information Technology*, *10* (6), 1494–1508. https://doi.org/10.32628/CSEIT241061187

Varshney, R. K., Pandey, N. K., Pandey, A. K. & Singh, A. N. (2025). Exploring Artificial Intelligence & Machine Learning Applications in Structural Engineering Trends and Challenges. *2025 International Conference on Next Generation Information System Engineering (NGISE)*, 1–6. https://doi.org/10.1109/NGISE64126.2025.11085231

Wala, R. (2025). An ethical framework for AI in structural engineering: from promise to practice. *The Structural Engineer*, *103* (10), 10. https://doi.org/10.56330/PTFH2233

Wang, Q., Dai, Y., Ma, Z., Ni, Y., Tang, J., Xu, X. & Wu, Z. (2022). Towards probabilistic data-driven damage detection in SHM using sparse Bayesian learning scheme. *Structural Control and Health Monitoring*, *29* (11). https://doi.org/10.1002/stc.3070

Xie, H., Mei, Q. & Chui, Y. H. (2025). AI applications for structural design automation. *Automation in Construction*, *179*, 106496. https://doi.org/10.1016/j.autcon.2025.106496

Zaker Esteghamati, M., Bean, B., Burton, H. V. & Naser, M. Z. (2025). Beyond Development: Challenges in Deploying Machine-Learning Models for Structural Engineering Applications. *Journal of Structural Engineering*, *151* (6). https://doi.org/10.1061/JSENDH.STENG-13301

Zhang, M., Guo, T., Zhu, R., Zong, Y., Liu, Z. & Xu, W. (2023). Damage identification of seismic-isolated structure based on CAE network using vibration monitoring data. *Engineering Structures*, *283*, 115873. https://doi.org/10.1016/j.engstruct.2023.115873

Zhang, Y., Ren, W., Chen, Y., Mi, Y., Lei, J. & Sun, L. (2024). Predicting the compressive strength of high-performance concrete using an interpretable machine learning model. *Scientific Reports*, *14* (1), 28346. https://doi.org/10.1038/s41598-024-79502-z

Zheng, H., Huang, Y., Wu, K., Wang, B., Hu, Q., Wang, D., Sun, B. & Antwi-Afari, M. F. (2025). A comparative analysis of explainable artificial intelligence (XAI) models for predicting concrete elastic dynamic modulus. *Smart Construction*. https://doi.org/10.55092/sc20250025

Kurcjusz, M., Das, R. R. (2025). Advances in structural engineering through artificial intelligence: methods, challenges and opportunities. *Acta Sci. Pol. Architectura*, *24*, 418–430, DOI: 10.22630/ASPA.2025.24.28

POSTĘPY W INŻYNIERII KONSTRUKCJI DZIĘKI SZTUCZNEJ INTELIGENCJI: METODY, WYZWANIA I MOŻLIWOŚCI

STRESZCZENIE

W artykule przedstawiono przegląd aktualnych zastosowań sztucznej inteligencji (AI) w inżynierii budowlanej ze szczególnym uwzględnieniem metod, wyzwań i perspektyw rozwoju. Omówiono, w jaki sposób techniki uczenia maszynowego, uczenia głębokiego i algorytmów ewolucyjnych zmieniają tradycyjne podejścia do projektowania, analizy i utrzymania konstrukcji. Integracja AI z BIM, bliźniakami cyfrowymi i systemami czujników przyczynia się do tworzenia bardziej zintegrowanego i opartego na danych środowiska inżynierskiego. Powszechne wdrożenie AI ograniczają jednak problemy z jakością danych, interpretowalnością modeli oraz brak ujednoliconych standardów walidacji. W opracowaniu podkreślono potrzebę rozwoju wyjaśnialnej sztucznej inteligencji, wprowadzenia nadzoru etycznego oraz standaryzacji danych, co umożliwi bezpieczne i odpowiedzialne wykorzystanie AI w praktyce inżynierskiej.

Słowa kluczowe: sztuczna inteligencja, uczenie maszynowe, uczenie głębokie, inżynieria konstrukcji, optymalizacja projektowania, monitorowanie stanu konstrukcji

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URBAN RENEWAL AND CULTURAL HERITAGE IN DATONG: A PATH TOWARD SUSTAINABLE DEVELOPMENT IN CHINA

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ABSTRACT

The revitalisation of the historic city centre of Datong in Shanxi Province, China, is a complex process of heritage protection, economic modernisation, and social transformation. In the 21st century, urban revitalisation projects were developed and implemented to rebuild the ancient city walls, restore historic spaces, and promote tourism as a driver of local development. These initiatives improved the city's image and infrastructure, but also presented numerous challenges related to authenticity, resettlement, and sustainable management. Datong was chosen as a case study because of its importance as an example of an industrial city transformed into a cultural and tourist centre. The study utilised terminological analysis and a literature review using databases such as Web of Science, Google Scholar, ResearchGate, and China National Knowledge Infrastructure (CNKI). In situ observations were also employed, allowing the authors to explore socio-spatial processes. The study situates Datong within the broader context of the evolution of urban revitalisation in China, from centralised to pluralistic, stakeholder-based governance. Understanding the complexity of these processes can provide a point of reference for other countries seeking a balance between heritage protection and contemporary development.

Keywords: urban revitalisation, Datong, cultural heritage, sustainable development, urban renewal, heritage conservation

INTRODUCTION

Revitalisation is a complex process encompassing spatial, social, cultural, and economic transformations. Culture-based urban renewal and urban revitalisation are being promoted worldwide. Cultural heritage is an important element in understanding a region's history and culture, as well as an embodiment of regional culture. Investing in resources and developing cultural heritage can bring numerous benefits to the environment, economy, and society. As Sheng, Liao, Xiong, Zhu and Cheung (2022) point out, numerous studies indicate that the activation and development of heritage are linked to the social environment. Authenticity is crucial for defining a historic landscape. As UNESCO pointed out in 2011, integrity and authenticity also require appropriate knowledge and planning tools. In recent years, the city of Datong, located in Shanxi Province, has become one of the most prominent examples of historic urban centre revitalisation projects in China. Datong has a rich history, stretching from the ancient settlement of Pingcheng – a strategically located city – through its

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development during the Ming and Qing dynasties, to its rapid industrialisation in the 20th century. Throughout its history, the city has served as an administrative, defensive, and commercial centre, reflected in its urban planning and historic monuments. Major challenges arose with the coal industry, which became a dominant economic factor (Xue, Zhang, Sun, Sun & Yang, 2021). Intensive industrialisation led to challenges in air quality and the condition of urban spaces. In the early 21st century, the authorities began a transformation toward heritage tourism, culminating in the revitalisation of the old town, the main stage of which was completed in 2016. This involved the reconstruction of the city walls and buildings in a historical style, a subject of discussion in academic literature. These activities enhanced the attractiveness of the space, but, as some researchers note, they also highlighted challenges related to preserving the authenticity of the heritage and the social continuity of the site (Audin, 2020; Lei & Zhou, 2022). The formal reconstruction process of Datong began around 2008, when the decision was made to reconstruct the central area of the city, including the city walls and historically styled buildings. The goal of these activities was to renew the urban fabric, improve the quality of life for residents, and develop tourism. The idea was to create a new identity for the city – a centre of cultural heritage in Shanxi Province. At the same time, the project sparked discussions about the authenticity and social consequences of revitalisation, as well as changes in the structure of the local economy. The aim of this article is to analyse the decisions made, the means used, the goals achieved, and the long-term effects of the revitalisation process, using the example of the Chinese city of Datong. The discussion places particular emphasis on discussing the decisions made and the new direction of sustainable design adopted after 2016, focused on ecology and identity.

MATERIAL AND METHODS

The city selection criterion was its significance as a case study in the transformation of an industrial city into a cultural and tourist centre. Datong (Shanxi Province, China) was chosen for its long history, diverse urban fabric, and extensive revitalisation efforts. It is also a representative example of China's approach to revitalising historic city centres, combining urban, social, and cultural aspects. This article utilises terminology analysis to systematise key concepts related to revitalisation, cultural heritage, and sustainable urban development. A literature review was conducted using the following databases: Web of Science, Google Scholar, ResearchGate, and China National Knowledge Infrastructure (CNKI). The research was immersive in nature; the authors observed the space in situ and analysed the social, economic, and societal processes occurring within it. The collected materials are supplemented by the authors' own photographs. The research approach is characterised by an interdisciplinary approach, combining urban planning, architectural, sociological, cultural, pro-ecological, and revitalisation aspects. The results and discussion section provides a spatial analysis of Datong's revitalisation efforts, a discussion of the social and economic impact of the transformation, and a discussion of heritage authenticity. The paper concludes with key findings regarding the effectiveness and limitations of revitalisation as an urban strategy.

RESULTS

Literature and terminology analysis

The Latin phrase "*re* + *vita*" literally means "to bring back to life", "to revitalise." The term "revitalisation" refers to activities carried out in existing urban areas. Revitalisation activities include the reconstruction of cities, old centres, degraded areas, and the restructuring of post-industrial and post-military areas. The Polish Revitalisation Act of 9 October 2015 defines revitalisation as the process of lifting degraded areas from a state of crisis, conducted comprehensively through integrated actions for the local community, space, and economy, focused on a territorial basis, and led by revitalisation stakeholders based on a municipal revitalisation program.

Stakeholders include, in particular, residents, owners, and perpetual usufructuaries of real estate (Ustawa z dnia 9 października 2015 r. o rewitalizacji). Revitalisation effects can also be achieved through surprise, culture, new technology, beauty, outstanding creative achievements, originality, magnificence, or splendour. The goal of urban renewal is harmonious and multifaceted development achieved by adapting old resources to new needs. The result is improved living conditions, the conservation of resources, and the integration of historic and contemporary buildings. The concept of renewal is the overarching definition. Revalorisation involves restoring the former value and appearance of neglected structures, as well as restoring the building to its original condition at the time of construction. Rehabilitation, a term frequently used in France, denotes the recovery of degraded buildings. This process may include: supplementing social infrastructure, stimulating the organisational forms of life and the personal activity of residents, renovations, and modernisations. Reconstruction is the restoration of the historic state based on existing documentation. These activities aim to remodel and introduce new elements into existing buildings while preserving the existing spatial layouts. The term "reconstruction" refers to the restoration or re-erection of something that has been destroyed. Modernisation is the modernisation and improvement of something. Renovation is the act of renovating or refreshing a building, for example, a façade.

The industrial revolution led to an increased demand for fossil fuel energy, and by the late 1960s, people began to pay attention to emerging environmental problems (Du, Wang & Feng, 2023). Rapid demographic and economic growth, along with the urbanisation trend of the 21st century, has led researchers and practitioners to incorporate environmental factors into urban development. The Chinese central and local governments are initiators of the development of sustainable cities. In 1994, the Chinese government adopted Agenda 21 (adopted at the 1992 UN Conference on Environment and Development in Rio de Janeiro), and the following year, sustainable development was recognised as the country's core strategy (Zhan, De Jong & De Bruijn, 2018). In 2015, the United Nations proposed Agenda 2030, marking a turning point in the global commitment to sustainable development. Implementing the 17 Sustainable Development Goals (SDGs) described in the document relies on the cooperation of governments around the world and requires the involvement of many stakeholders (Zhou & Dai, 2024). Chmielewski (2010) emphasises that sustainable development should maintain a balance between the needs of current and future generations. He also points to the necessity of interdependence between economic needs and environmental protection needs (Chmielewski, 2010). Sustainable construction involves limiting the negative impact of construction on the environment while simultaneously striving to improve the quality of life (Piętocha, Li & Koda, 2025). Architects and urban planners worldwide should protect the ecosystem and maintain key resources (Piętocha, 2024).

History of Datong

Present-day Datong, historically known as Pingcheng (平城), was a settlement of strategic importance in ancient times, but its prosperity began only after it was established as the capital of the Northern Wei Dynasty around 398 AD. Located in a basin surrounded by the Hengshan Mountains, the city was fortified with rammed-earth walls and planned along a North-South axis, with a clear division between palace and residential areas. This layout combined Chinese urban traditions with elements of steppe culture, reflecting the origins of the Northern Wei rulers. After the capital was moved to Luoyang (494 AD), Pingcheng lost its political significance, but its structure and fortifications became a model for later cities in northern China. During this time, the city retained its strategic role as a defensive point on China's northern border, protecting the empire from nomadic raids and controlling trade routes toward Mongolia throughout the Tang Dynasty (618–907) (Guo, 2019). During the Liao Dynasty (907–1125) and Jin Dynasty (1115–1234), Datong gradually regained its position in the region. Parts of the fortifications were rebuilt, and new city quarters were incorporated into the urban plan. During the Yuan Dynasty (1271–1368), Datong became a major trading centre on the route, connecting China's agricultural zones with the steppe regions (Zhang, 2010). During the Ming

Dynasty (1368–1644), the city walls were completely reconstructed and completed in 1372, giving the city its rectangular layout, largely preserved to this day (Lu, 2014). The walls, with their four main gates, were part of the empire's extensive defensive policy against invasions from the north (Zhang, 2010). Thanks to its location on military and trade routes, Datong once again became a significant administrative and commercial centre. It retained this position during the last Chinese dynasty, the Qing (1644–1911). In the 20th century, Datong developed into one of China's major mining cities, dominated by the coal industry and a railway infrastructure connecting the city with Beijing and Tianjin (Gu, Wu & Xie, 2022).

The aim of revitalisation

The process of transforming Datong into an industrial centre was linked to the recognition of Shanxi Province as one of China's most important mining regions. After 1949, with the establishment of the People's Republic of China, Datong became a priority centre for industrialisation in northern China. The development of mining, energy, and transportation infrastructure (railways connecting the city with Beijing and Tianjin) contributed to the city's dynamic growth, earning it the nickname China's "coal heartland" (Lei, 2022). In the following decades, until the 1980s, Datong based its economy on coal mining and processing, which shaped its spatial and social structure. Industrialisation fostered the development of workers' settlements and population growth, while simultaneously posing new challenges for environmental protection and residents' quality of life (He, 2018). Since the 1990s, as a result of falling global coal prices, rising mining costs, and economic reforms that limited state subsidies, Datong's existing model has gradually begun to lose its stability. This led to a period of serious economic and social hardship, including rising unemployment, population migration, and deteriorating environmental quality (Gu et al., 2022). Furthermore, poor air quality and deteriorating urban spaces have contributed to the perception of Datong as a site facing challenges related to industrialisation and environmental protection (Audin, 2020). As a result, the city was included in the national resource-based cities transformation programme, the aim of which was to diversify the economy and reshape Datong from a mining centre to a centre for cultural tourism, heritage, and green energy (Gu et al., 2022). This project was part of a broader strategy of the Chinese municipal authorities, combining urban renewal with the promotion of heritage and historical aesthetics as a means of economic revitalisation, improving the city's image, and attracting investors and tourists. In the case of Datong, revitalisation was not only a material process but also a tool for redefining urban identity – transitioning from a "coal city" to a "heritage city". As a result, since the late 2000s, Datong has consistently promoted itself as a "city of historical renaissance", whose space evokes the aesthetics of former dynasties and supports the construction of a new urban identity (Audin, 2020; Lei & Zhou, 2022). Implementing Datong's revitalisation programme involved extensive spatial, economic, and social measures. Following the collapse of the mining sector in the 1990s, caused by the collapse of many mines due to falling commodity prices and reduced state subsidies, the city was included in the government's resource-based cities restructuring programme. Within this framework, central and local authorities conducted a process of planned closure of unprofitable coal mines and the consolidation of mining enterprises, aimed at diversifying the economic structure and reducing the industry's negative impact on the natural environment (National Development and Reform Commission [NDRC], 2013; He, 2018; Gu et al., 2022). The second step, constituting the most visible aspect of the spatial transformation, was the extensive reconstruction of the city centre. Between 2008 and 2016, modernisation and urban transformation were carried out, eliminating post-war and industrial buildings to create space for a new spatial layout (Lei, 2022). As Lei and Zhou note, these activities were a comprehensive reconstruction, aimed at creating an urban space that corresponded to contemporary notions of a "traditional Chinese city". The centrepiece of the programme was the reconstruction of the city walls and the creation of the so-called new old city – a stylised urban space reflecting the architecture of the Ming and Qing dynasties. The project included the reconstruction of four

city gates, the construction of new watchtowers, and streets with an axial layout consistent with the principles of classical Chinese urbanism (Lei & Zhou, 2022). This undertaking significantly improved the city's visual image and became an important element of its tourism promotion. However, as some researchers emphasise, it sparks debate about the relationship between the aestheticisation of the past and the authenticity of heritage (Audin, 2020).

Effects of Datong's revitalisation

The Datong revitalisation programme has yielded complex and multifaceted results, encompassing both significant achievements and diverse opinions regarding its impact. From an urban planning and aesthetic perspective, the project significantly improved the quality of public space and urban infrastructure. The reconstruction of the city walls (Fig. 1), street revitalisation (Fig. 2), improved transportation systems, and the introduction of modern infrastructure solutions have raised the standard of living of residents and strengthened the attractiveness of the city's central areas. The revitalisation also had a significant impact on Datong's image – Datong was promoted as a "city of heritage", and the renovated city centre became a showcase for Shanxi Province and an example of China's cultural tourism development policy (Lei & Zhou, 2022). The revitalisation positively influenced the diversification of the local economy. Increased investment in the service and tourism sectors contributed to the creation of new jobs, particularly in the hotel, restaurant, and cultural sectors (He, 2018). Combined with actions to limit coal mining, these initiatives improved air quality and environmental conditions, which was one of the long-term goals of the transformation (Gu et al., 2022). The preservation of material heritage was also of particular importance in the revitalisation process of Datong. During the revitalisation process, some authentic historic buildings, such as the Huayan Temple Complex (Fig. 3) and the Shanhua Pagoda, were placed under conservation protection and incorporated into the new urban layout as key cultural heritage landmarks (Wang, 2020). At the same time, many former urban structures, especially from the post-war period, were demolished and rebuilt in a historical style, often using modern materials and construction techniques. As Lei notes, the result was a "city with a dual identity" – combining authentic monuments with newly constructed, stylised structures. This was one of the long-term goals of the transformation (Gu et al., 2022; Lei & Zhou, 2022).



Fig. 1. Datong city walls, 2024

Source: photos by the authors.

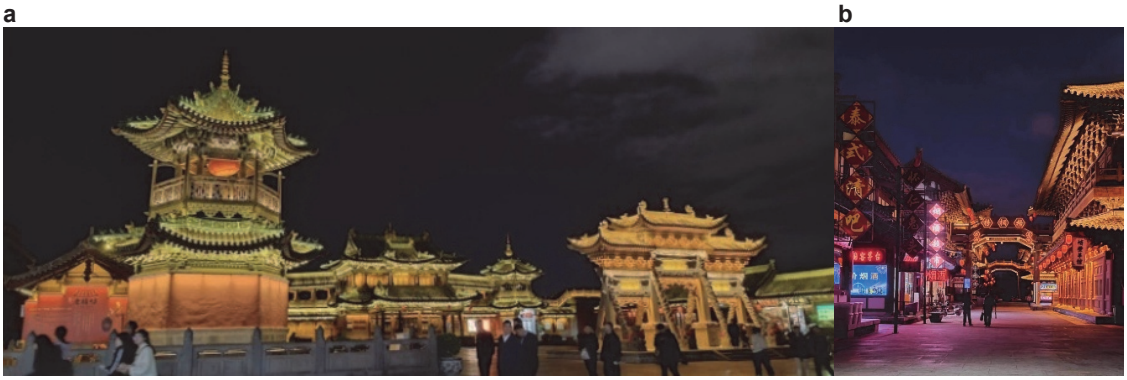


Fig. 2. Datong in 2024: Qipan Street area – example of a stylised structure (a) and one of the restored streets of Datong Old Town (b)

Source: photos by the authors.

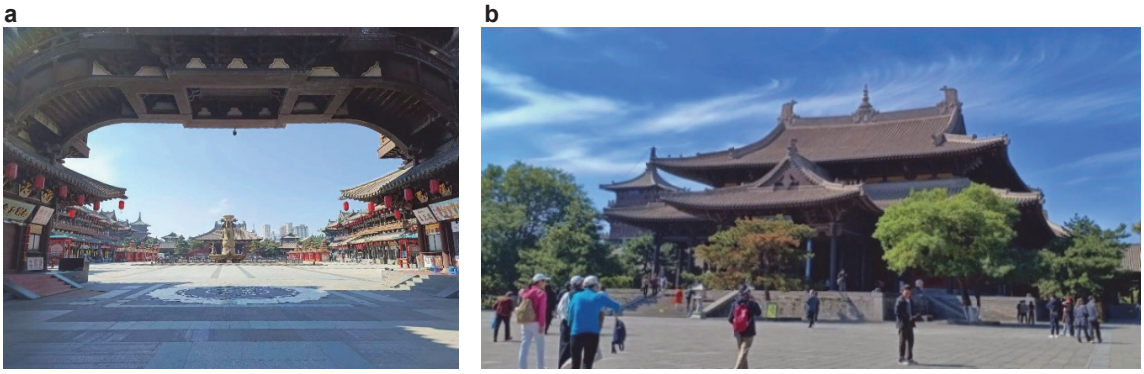


Fig. 3. Huayan Temple in 2024: view of the restored square (a) view on the surroundings – new, stylised buildings were built around the monument (b)

Source: photos by the authors.

At the same time, some newly created spaces remained underpopulated (in the literature, this phenomenon is referred to as ghost towns). This is due to high maintenance costs and limited resident influx. This phenomenon has highlighted the challenges associated with spatial reconstruction projects based primarily on aesthetics (Lei & Zhou, 2022). From a cultural perspective, revitalisation has contributed to strengthening heritage awareness and promoting local culture, but it has also sparked an academic debate on the concept of authenticity. Audin and Wang note that the case of Datong can be interpreted as an example of the "aestheticisation of history" and "managed heritage". Despite emerging tensions and debates, Datong's revitalisation is considered an important urban planning experiment on a national scale, demonstrating the potential of integrating heritage protection with the development of tourism and the urban economy (Audin, 2020; Wang, 2020).

DISCUSSION

Revitalisation in the People's Republic of China

Since the founding of the People's Republic of China in 1949, the country has achieved significant success in economic development, environmental improvement, infrastructure construction, and poverty alleviation. Urban revitalisation has played a significant role in China's economic development and continues to evolve with the changing needs of urban development. As Zhu, Song, and Bai emphasise, by the end of the 20th century, the real estate market became a key driver of urban revitalisation. In the 1990s, a series of regulations and laws were widely adopted that initiated urban revitalisation. Simultaneously, local governments published policies encouraging social capital to invest in urban revitalisation (Zhu, Song & Bai, 2024). Xie, Zheng, Zhai, Yuan and Qiming (2024) emphasise that China's urbanisation process is currently in a transition phase – from rapid to slow growth – and urban revitalisation is one of the fundamental mechanisms for achieving sustainable urban development in China, receiving considerable attention. Revitalisation promotes the reuse of abandoned buildings and land, improves energy efficiency and the natural environment, and engages multiple stakeholders. However, conflicting interests can lead to social risks (Xie et al., 2024). Chen, Zhou, Huang and Ye (2021) divide urban revitalisation in China into four stages, resulting from the perspective of governance. They specify: unitary governance, binary governance, tripartite governance, and pluralistic co-governance (Chen et al., 2021). In the literature, neighbourhood regeneration is referred to as "urban revitalisation", "urban renewal", or "urban regeneration" (Zabielaitė-Skirmantė, Burinskienė & Maliene, 2023).

The example of Datong, 2008–2016

Despite its ambitious goals and visual successes, Datong's revitalisation programme became the subject of intense debate in academic, media, and social circles. Discussions focused primarily on the authenticity of the recreated urban space. Many of the reconstructed old city quarters were built from scratch, using modern technologies and materials, which, as Lei and Zhou note (2022), gave them a symbolic rather than historical character. This approach is sometimes referred to as "heritage aestheticisation", in which the historic form serves a representative and educational function, not necessarily reflecting the original urban fabric or serving as a carrier of the memory of the place (Lei & Zhou, 2022). From a social perspective, the Datong revitalisation process involved the relocation of residents and the transformation of local neighbourhood structures. The relocation of people to new, peripheral neighbourhoods entailed adaptation challenges, changing existing social relationships, and changing daily lifestyles (He, 2018). As Audin notes (2020), these activities led to the creation of a "dual city" system, encompassing a representative part dominated by tourism and residential functions, where the daily lives of residents are concentrated. Economically, the project required significant financial outlays, primarily from loans and public funds, which led to a burden on the city budget (Wang, 2020). Public debate suggested that these funds could have been used, for example, to improve social conditions, education, or industrial modernisation (Gu et al., 2022). At the same time, supporters of the project emphasised its long-term value – building the city's image, cultural tourism, and improving the living environment (Lei & Zhou, 2022).

New directions for Datong's development after 2016

After 2016, after analysing the experience of the previous revitalisation phase and facing new financial constraints, the Datong authorities began redefining the city's development strategy. The focus shifted from monumental reconstruction to the protection of authentic tangible and intangible heritage. New city plans, aligned with the guidelines of the National Cultural Heritage Administration, emphasise the importance of preserving the original substance of historical monuments and integrating heritage protection into the life of the contemporary city (Wang, 2020).

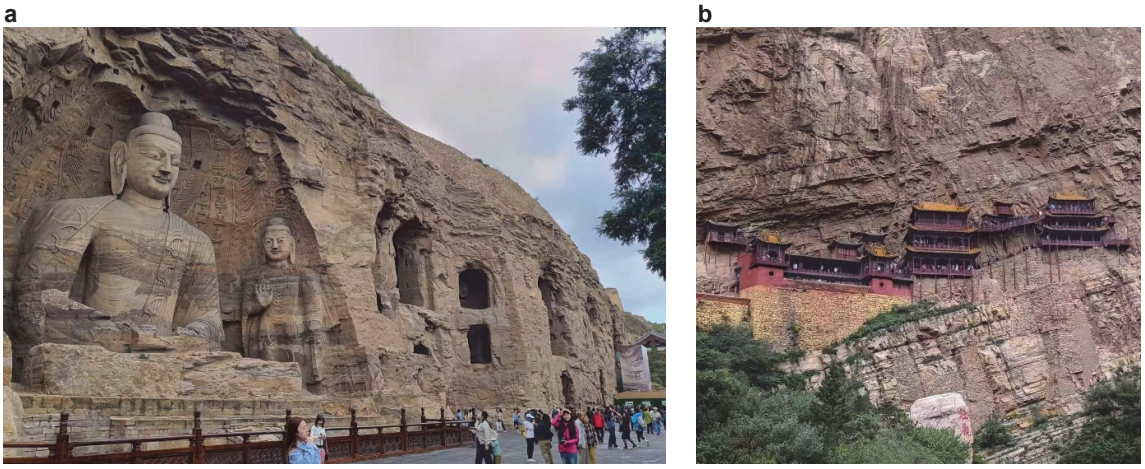


Fig. 4. The UNESCO World Heritage Sites of the Shanxi Province in 2024: Yungang Grottoes, mostly built between 460–525 during the Northern Wei Dynasty, located about 17 km northwest of Datong City (a), and Hanging Temple, located about 80 km southeast of Datong City (b)

Source: photos by authors.

Local authorities are placing greater emphasis on the conservation and adaptation of existing sites, such as the Huayan and Shanhua temple complexes and the historic streets near the former city walls, rather than their complete reconstruction (Lei, 2022). Simultaneously, a number of initiatives were introduced for sustainable tourism development and revitalisation through culture. This strategy assumed a shift from mass tourism to quality tourism, focusing on authentic experiences, local culture, and ecology. Projects such as the Datong Cultural Green Belt and the Cultural Revitalisation through Heritage programme promote the integration of tourism with education and environmental protection (Gu et al., 2022). The city government, in collaboration with universities and community organisations, is also developing green energy and sustainable infrastructure initiatives, striving to connect cultural heritage with a modern low-carbon economy (He, 2018). This new approach is based on the belief that true revitalisation is not simply about restoring form but also about restoring the meaning and social function of a place. As Lei and Zhou emphasise (2022), the shift in urban policy in Datong represents a shift from "symbolic reconstruction" to "living heritage", in which heritage becomes an integral element of residents' identity and daily life.

CONCLUSIONS

The case of Datong has become a point of reference for a broader reflection on contemporary understandings of heritage in China. It has revealed the existing tensions between authenticity and representativeness, between economic development and social integration, and between cultural identity policy and economic realities. Datong can be seen as a kind of laboratory for the Chinese approach to heritage – a place where history has been integrated with spatial planning processes and the city's image strategy. More broadly, revitalisation in China demonstrates the complexity of the relationship between the state, local community, and the market. The evolution from unitary governance to pluralistic co-governance reflects the gradual integration of more stakeholders into planning processes. As the pace of urbanisation slows, the importance of spatial quality, heritage, and sustainable development is clearly increasing, making revitalisation one of the key tools

of 21st-century urban policy. Research on Chinese methods of managing urban revitalisation, its successes, and its challenges, can provide a benchmark for other countries seeking a balance between heritage protection and modernisation. The case of Datong's revitalisation, based on its cultural heritage, could become a catalyst for the transformation of post-industrial cities worldwide. Future efforts should focus on the need for interdisciplinary action, public participation, and integrating revitalisation issues with a long-term regional development strategy. All projects and implementations should be conducted in accordance with the principles of sustainable development.

Authors' contributions

Conceptualisation: A.P. and M.O.G.; methodology: A.P.; validation: A.P. and M.O.G.; formal analysis: A.P. and M.O.G.; investigation: A.P. and M.O.G.; resources: A.P. and M.O.G.; data curation: A.P. and M.O.G.; writing – original draft preparation: A.P. and M.O.G.; writing – review and editing: A.P. and M.O.G.; visualisation: A.P. and M.O.G.; supervision: A.P.; project administration: A.P.; funding acquisition: A.P.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Audin, J. (2020). The Coal Transition in Datong: An Ethnographic Perspective. *Made in China Journal*, *5* (1), 34–43. https://doi.org/10.22459/MIC.05.01.2020.04

Chen, M., Zhou, Y., Huang, X. & Ye, C. (2021). The Integration of New-Type Urbanization and Rural Revitalization Strategies in China: Origin, Reality and Future Trends. *Land*, *10* (2), 207. https://doi.org/10.3390/land10020207

Chmielewski, J. M. (2010). *Teoria urbanistyki w projektowaniu i planowaniu miast* (rev. ed.). Warszawa: Oficyna Wydawnicza Politechniki Warszawskiej.

Du, C., Wang, C. & Feng, T. (2023). The Impact of China's National Sustainable Development Experimental Zone Policy on Energy Transition. *Sustainability*, *15* (10), 8315. https://doi.org/10.3390/su15108315

Gu, Q., Wu, Z. & Xie, D. (2022). Transformation and Development of Resource-Based Cities in China: A Review and Bibliometric Analysis. *Frontiers in Environmental Science*, *10*, 975669. https://doi.org/10.3389/fenvs.2022.975669

Guo, J. (2019). Historical Geography, Place Names, and Their Implications for Northern Wei Dynasty. In *Spatial Transformations and Urban Form in Pingcheng (Datong) during the Northern Wei Dynasty* (pp. 41–42). Boston: Boston University.

He, S. (2018). Resource-Dependent Cities and Sustainable Transition: The Case Datong. *Urban Studies*, *55* (6), 1309–1325.

Lei, H. (2022). *Spatial Transformations and Urban Form in Pingcheng (Datong) during the Northern Wei Dynasty* (PhD dissertation). University of Sheffield, Sheffield.

Lei, H. & Zhou, Y. (2022). Conducting Heritage Tourism-Led Urban Renewal in Chinese Historical and Cultural Urban Spaces: A Case Study of Datong. *Land*, *11* (12), 2122. https://doi.org/10.3390/land11122122

Lu, Y. (2014). Reconstruction of the Datong City Walls in the Early Ming Dynasty. *Architectural History Review*, *12* (2), 88–90.

National Development and Reform Commission [NDRC]. (2013). *National Plan for Sustainable Development of Resource-Based Cities (2013–2020)*. Beijing: NDRC Publications.

Piętocha, A. (2024). The BREEAM, the LEED and the DGNB Certifications as an Aspect of Sustainable Development. *Acta Scientiarum Polonorum. Architectura*, *23*, 121–133. https://doi.org/10.22630/ASPA.2024.23.9

Piętocha, A., Li, W. & Koda, E. (2025). The Vertical City Paradigm as Sustainable Response to Urban Densification and Energy Challenges: Case Studies from Asian Megacities. *Energies*, *18* (19), 5278. https://doi.org/10.3390/en18195278

Sheng, G., Liao, L., Xiong, L., Zhu, B-W. & Cheung, S. M. (2022). Revitalization and Development Strategies of Fostering Urban Cultural Heritage Villages: A Quantitative Analysis Integrating Expert and Local Resident Opinions. *Systems*, *10* (6), 202. https://doi.org/10.3390/systems10060202

Ustawa z dnia 9 października 2015 r. o rewitalizacji. Dz.U. 2024, poz. 278.
Wang, J. (2020). Cultural Heritage Conservation and Urban Renewal in Datong City. *Journal of Asian Architecture and Building Engineering*, *19* (5), 487–495
Xie, H., Zheng, S., Zhai, Y., Yuan, J. & Qiming, L. (2024). Unveiling Urban Regeneration Risks in China: A Social Perspective. *Sustainability*, *16* (4), 1671. https://doi.org/10.3390/su16041671
Xue, M., Zhang, X., Sun, X., Sun, T. & Yang, Y. (2021). Expansion and Evolution of a Typical Resource-Based Mining City in Transition Using the Google Earth Engine: A Case Study of Datong, China. *Remote Sensing*, *13* (20), 4045. https://doi.org/10.3390/rs13204045
Zabielaitė-Skirmantė, M., Burinskienė, M. & Maliene, V. (2023). Influence of Revitalization on the Social and Economic Well-Being of Residents: Case Study of Lithuania. *Sustainability*, *15* (9), 7304. https://doi.org/10.3390/su15097304
Zhan, C., De Jong, M. & De Bruijn, H. (2018). Funding Sustainable Cities: A Comparative Study of Sino-Singapore Tianjin Eco-City and Shenzhen International Low-Carbon City. *Sustainability*, *10* (11), 4256. https://doi.org/10.3390/su10114256
Zhang, Q. (2010). Urban Morphology and Frontier Functions of Datong in the Yuan Dynasty. *Journal of Chinese Historical Geography*, *25* (3), 45–57.
Zhou, D. & Dai, H. (2024). Provincial Sustainable Development in China from a Multidimensional Perspective: Regional Differences, Dynamic Evolution, Spatial Effects, and Convergence. *Sustainability*, *17* (1), 215. https://doi.org/10.3390/su17010215
Zhu, Y., Jusheng, Song, J. & Bai, Y. (2024). China's Urban Regeneration Evolution from 1949 to 2022: From the Perspective of Governance Mode. *Land*, *13* (11), 1806. https://doi.org/10.3390/land13111806

ODNOWA MIEJSKA I DZIEDZICTWO KULTUROWE W DATONGU: DROGA DO ROZWOJU ZRÓWNOWAŻONEGO W CHINACH

STRESZCZENIE

Rewitalizacja historycznego centrum miasta Datong w prowincji Shanxi w Chinach jest złożonym procesem ochrony dziedzictwa, modernizacji gospodarczej i transformacji społecznej kraju. W XXI wieku opracowano i zrealizowano rewitalizacje miejskie mające na celu odbudowę starożytnych murów miejskich, odrestaurowanie przestrzeni zabytkowych i promowanie turystyki jako siły napędowej rozwoju lokalnego. Wymienione inicjatywy poprawiły wizerunek i infrastrukturę miasta, choć proces wiązał się z wieloma wyzwaniami dotyczącymi autentyczności, przesiedleń i zrównoważonego sposobu zarządzania. Datong wybrano jako studium przypadku ze względu na jego reprezentatywność – miasto przemysłowe przekształcone w ośrodek kulturalny i turystyczny. W badaniu wykorzystano analizę terminologiczną, przeprowadzono przegląd literatury z wykorzystaniem baz danych, takich jak: Web of Science, Google Scholar, ResearchGate i China National Knowledge Infrastructure (CNKI). Zastosowano również obserwacje in situ – pozwalającą autorkom na eksplorację procesów społeczno-przestrzennych. Badanie sytuuje Datong w szerszej perspektywie ewolucji rewitalizacji miast w Chinach – od scentralizowanego do pluralistycznego sposobu zarządzania opartego na interesariuszach. Zrozumienie złożoności procesów może stanowić punkt odniesienia dla innych krajów poszukujących równowagi pomiędzy ochroną dziedzictwa a współczesną zabudową.

Słowa kluczowe: rewitalizacja miejska, Datong, dziedzictwo kulturowe, rozwój zrównoważony, odnowa miejska, ochrona dziedzictwa

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THE IMPACT OF RECREATIONAL BOATING ON WATER QUALITY AND THE ECOSYSTEMS OF THE BATA CANAL

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ABSTRACT

The aim of the study was to evaluate the impacts of recreational boat traffic on the water quality and ecological status of the Bata Canal (Czech Republic), an important tourist waterway in South Moravia. Field measurements of physicochemical water parameters (COD_{Cr}, NO_3^- N, P_{tot}, pH, EC, DO) and an on-site questionnaire survey among canal users were carried out. The results showed that recreational boat traffic does not cause measurable deterioration of water quality, even in the most intensively used sections. The highest values of dichromate chemical oxygen demand (up to 23.4 $mg \cdot l^{-1}$) and total phosphorus (0.2 $mg \cdot l^{-1}$) were recorded in Veselí nad Moravou, while all values remained below Czech surface-water guideline thresholds. The findings highlight the role of natural self-purification processes, hydrological conditions, and responsible visitor behaviour in maintaining water quality. From a landscape-planning perspective, the study emphasises zoning, bank management, and operational regimes as elements of blue-green infrastructure supporting ecological stability. The Bata Canal represents a successful example of coexistence between recreation and aquatic ecosystem protection, showing that under current recreational use, good ecological conditions can be sustained through appropriate management and user awareness.

Keywords: Bata Canal, recreational boating, water quality, eutrophication, environmental management, landscape planning, blue-green infrastructure

INTRODUCTION

The development of recreational navigation on inland waterways in Europe not only brings economic benefits (Calderón-Rivera, Bartusevičienė & Ballini, 2024a) but also poses a significant challenge in terms of sustainable development and for the protection of aquatic ecosystems (Calderón-Rivera, Bartusevičienė & Ballini, 2024b). According to Mako and Galieriková (2021), inland navigation, especially on large European rivers such as the Danube and the Rhine, is of increasing importance for regional economies and tourism. At the same time, however, this trend requires comprehensive management of the environmental impacts associated with the increase in recreational traffic, as well as the development of ports and infrastructure (Schafft, Wegner, Meyer, Wolter & Arlinghaus, 2021).

Current research shows that the interconnection of inland and coastal waterways in the context of climate change may increase environmental risks, such as eutrophication, biodiversity loss, and disruption of the hydrological balance (Némethy, Ternell, Bornmalm, Lagerqvist & Szemethy 2022). Sexton et al.

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(2024) further highlight that the combination of shipping and land-use change negatively affects freshwater biodiversity in Europe, especially for species sensitive to erosion and chemical stresses.

Inland waterways, including those with historical significance, are therefore understood as linear infrastructures that combine transport and ecological functions (Steege et al., 2022). Sustainable management of these systems requires a balance between recreational use and the protection of ecosystem services (Afentou et al., 2022; Arif, Behzad, Tahir & Changxiao, 2022). In the context of landscape planning and architectural design, the visual and spatial quality of the water corridor, the legibility of nodes (piers, footbridges, platforms), and their material and vegetation integration into the surrounding landscape are also gaining importance.

The 53 km long Bata Canal is a unique example of the connection between technical cultural heritage and natural habitat. It was built in the 1930s to transport lignite and irrigate agricultural landscapes, but after the end of its industrial use, it was gradually revitalised into a recreational and tourist waterway. Today, it serves mainly for the purposes of water tourism, recreational boating, and regional tourism, thus becoming a model example of adaptive reuse of technical structures in the landscape (Machar, 2013). From the perspective of landscape ecology, the canal represents an important linear ecosystem, combining natural and artificial sections, slow-flowing and stagnant waters, and extensive littoral zones with wetland vegetation. This mosaic character supports biodiversity and the aesthetic value of the area, but, at the same time, increases its vulnerability to recreational loads and changes in the hydrological regime. In recent years, the Bata Canal has also become a subject of interest from the perspective of landscape and visual planning. The study by Jiang et al. (2025) emphasises that cultural heritage waterways have a high potential for sustainable development and ecotourism if their management is based on the integration of aesthetic, ecological and social functions. The Bata Canal can thus be perceived not only as a transport and tourist route, but also as a cultural landscape corridor that mediates the relationship between humans and the aquatic environment in the conditions of a changing climate and increasing tourist pressure (Fig. 1).

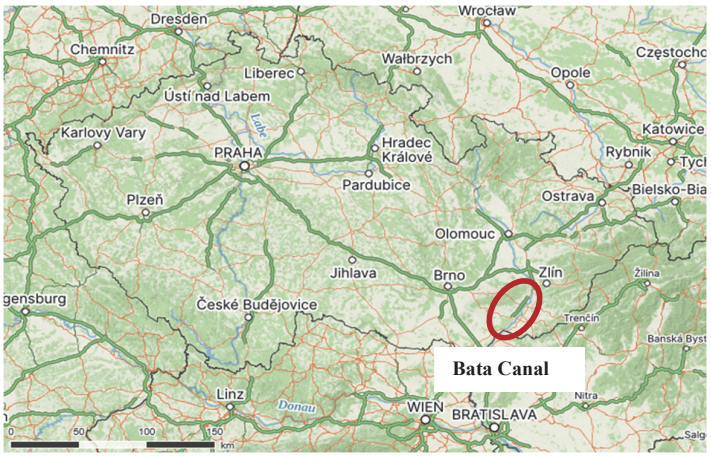


Fig. 1. Area of interest in Czech Republic

Source: ©Seznam.cz, edited by authors.

The aim of this study was to verify whether the current intensity of recreational boat traffic affects the water quality and ecological processes of the Bata Canal. The hypothesis assumed that at the current level of tourism, there is no significant deterioration of the physicochemical parameters of the water, with the key factors being

the tributaries from the Morava basin and agricultural activity in the vicinity. The secondary aim is to interpret the environmental results in terms of landscape-architectural planning and to propose principles for spatial and operational management of the riverbank sections and docks.

MATERIAL AND METHODS

Site characteristics,

The Bata Canal is a significant waterway in South Moravia (Czech Republic), connecting the Morava River between Otrokovice and Rohatec, with a total length of 53 km. It was built in the 1930s to supply water to the Bata industrial enterprises and to irrigate agricultural land. Today, it is used mainly for recreational boating and water tourism.

The channel has the character of a shallow, slow-flowing stream with a width of 10–12 m and a depth of 1.5–2.5 m. The water body is formed by alternating natural sections of the Morava River and artificially constructed branches. The banks are partially fortified, in places with natural growth of reed (*Phragmites australis*) and cattail (*Typha latifolia*), which contribute to the self-cleaning capabilities of the system. The surrounding landscape is used for agriculture, and there are several smaller villages, recreational docks, and campsites nearby (Fig. 2).



Fig. 2. Boating season on the Bata Canal

Source: authors.

Selection of sites and sampling

Field sampling was carried out during the main boating season (April–October 2022) at five representative sections of the Bata Canal: Veselí nad Moravou, Vnorovy, Strážnice, Výklopník and Rohatec. These sites represent different levels of recreational load and hydrological conditions along the canal. At each site, surface water samples were collected approximately 0.5 m below the water surface from the central part of the channel profile to minimise bank effects. Sampling was conducted monthly. Water samples (1 L) were collected into clean polyethylene bottles, stored in a portable cooler, and transported to the laboratory for analysis on the day of sampling (Fig. 3).



Fig. 3. Simple profiles on the Bata Canal

Source: © Seznam.cz, edited by authors.

Laboratory analyses

The following physicochemical parameters were analysed:

- pH [-], according to CSN EN ISO 10523 (Czech Standardisation Agency [ČAS], 2012a), and water temperature [°C] with a portable Hach HQ40d,
- dissolved oxygen (DO) [mg·l^{-1}], electrochemical probe method according to standards ČSN EN 25814 and ČSN EN ISO 5814 (ČAS, 1993a, ČAS, 2012b),
- electrical conductivity (EC) [mS·m^{-1}], conductometric method according to ČSN EN 27888 (ČAS, 1993b),
- dichromate chemical oxygen demand (COD_{Cr}) [mg·l^{-1}], dichromate method according to ČSN ISO 6060 (ČAS, 1996),
- nitrate nitrogen (NO_3^-N) [mg·l^{-1}], spectrophotometry according to ČSN EN ISO 13395 (ČAS, 1997),
- total phosphorus (P_{tot}) [mg·l^{-1}], spectrophotometry after mineralisation according to ČSN EN ISO 6878 (ČAS, 2004).

All analyses followed Czech quality standards for surface water.

Data processing

Measured data were evaluated using descriptive statistics (mean values). Results were interpreted in relation to Czech surface water quality classifications (Table 1).

Table 1. Water quality indicators and their classification according to ČSN 75 7221 (ČAS, 2017)

Indicator	Unit	Class I	Class II	Class III	Class IV	Class V
Conductivity (EC)	$mS \cdot m^{-1}$	< 40	< 70	< 110	< 160	≥ 160
Dissolved oxygen (DO)	$mg \cdot l^{-1}$	> 8.5	> 7.5	> 6	> 4	≤ 4
Nitrate nitrogen (NO_3^- N)	$mg \cdot l^{-1}$	< 2.5	< 5	< 8	< 12	≥ 12
Dichromate chemical oxygen demand (COD_{Cr})	$mg \cdot l^{-1}$	< 15	< 25	< 45	< 60	≥ 60
Total phosphorus (P_{tot})	$mg \cdot l^{-1}$	< 0.05	< 0.15	< 0.3	< 0.6	≥ 0.6

Class I – unpolluted water, Class II – slightly polluted water, Class III – polluted water, Class IV – heavily polluted water, Class V – extremely polluted water.

Source: own work.

Questionnaire survey

The research also included a short on-site questionnaire survey focused on visitors' attitudes toward the protection of the aquatic environment and basic boating behaviour (Fig. 4). The survey was conducted in August 2022 at the Petrov lock during the main boating season. A total of 15 respondents participated. The questionnaire consisted of six simple questions concerning visit frequency, group size, route choice, onboard waste handling and general environmental awareness. The purpose of the survey was to obtain indicative information on visitor responsibility and awareness in relation to the protection of water quality in the Bata Canal.



Fig. 4. Questionnaire survey process

Source: photo by authors.

Field observations

In parallel with the questionnaire survey, systematic field observations were conducted focusing on: (i) the cleanliness of the banks and docks, (ii) the presence of litter on the water surface, (iii) the intensity of navigation traffic (in number of boats per hour), and (iv) visible signs of pollution (oil stains, turbidity,

foam). Observations were carried out three times a week for six weeks (July–August). Field notes included a visual assessment of boating frequency and bank cleanliness.

RESULTS

Water quality and spatial differences

The measured results (Table 2) confirmed that the water in the canal has a stable quality for most indicators corresponding to water quality Classes I–II. Only the TP indicator values show water quality Class III. The slight increase in COD_{Cr} and P_{tot} in the middle part of the canal (Veselí nad Moravou) can be attributed to a combination of lower flow, more intensive tourist traffic and local inflows from urbanised areas. Spatial patterns were interpreted descriptively based on measured average values. The results show that recreational boat traffic currently has a negligible influence on basic water quality indicators.

Table 2. Seasonal average values of physicochemical water parameters on the Bata Canal (April–October 2022)

Location	Nitrate nitrogen (NO_3^- N) [mg·l^{-1}]	Total phosphorus (P_{total}) [mg·l^{-1}]	Dichromate chemical oxygen demand (COD_{cr}) [mg·l^{-1}]	Dissolved oxygen (DO) [mg·l^{-1}]	pH [-]	Conductivity (EC) [mS·m^{-1}]
Veselí nad Moravou	3.07	0.2	20.1	9.5	8.2	46
Vnorovy	2.01	0.17	22.3	11.09	8.1	45
Strážnice	2.1	0.13	21.5	7.05	8.3	48
Výklopník	2.12	0.19	23.4	10.26	8.0	60
Rohatec	2.11	0.18	20.0	8.98	8.4	48

Source: own work.

Self-cleaning processes and ecological stability

Due to the slow flow and the presence of macrovegetation (*Ph. australis*, *T. latifolia*), the channel exhibits the ability of biological filtration and nutrient accumulation. Plants in the littoral zone act as biofilters, contributing to the reduction of nitrate and phosphorus content. The presence of periphyton and small aquatic animals indicates a stable ecological balance. No signs of massive cyanobacterial development or hypoxia were observed, confirming the good trophic stability of the system.

Tourist burden and user behaviour

Questionnaire results show a high level of environmental responsibility. Only a small proportion of users reported water pollution (12%). Subjective perception of the state of the environment correlates with objective data – areas with higher visitor numbers did not show higher nutrient concentrations. Local pollution in the marinas (especially from the operation of refreshments) remains a problem, which requires regular waste collection and supervision.

Climate change connection

Due to climate change and longer periods of drought, reduced flows can be expected, which may increase the risk of eutrophication in the future. Therefore, it is necessary to continue long-term monitoring and optimisation of channel management with respect to the hydrological regime.

DISCUSSION

Main implications of the findings

A set of physicochemical indicators (COD_{Cr}, NO_3^- N, P_{total}, pH, EC, DO) demonstrated stable water quality corresponding to Class II, with no clear spatial deterioration along the canal. Slightly higher values of COD_{Cr} and P_{total} in Veselí nad Moravou can be attributed with high probability to local tributaries and hydrological conditions (lower dilution effect, longer residence times), not to recreational navigation itself. These results support the working hypothesis that the current intensity of recreational traffic on the Bata Canal does not have a detectable negative impact on basic water quality parameters. From the perspective of corridor planning, this means that the key to sustainability does not lie in area-wide restrictions on navigation, but in targeted management of point and line "inflows" and in fine-tuning of operational rules in time and space.

Comparison with the literature: what impacts can be expected and when

The findings are consistent with framework reviews that low- to moderate-intensity aquatic recreation has limited impact on chemical parameters if self-cleaning processes are functioning and basic management is applied (Venohr et al., 2018; Steege et al., 2022). At the same time, however, syntheses and meta-analyses point out that the ecological impacts of recreation tend to be underestimated, spatially and temporally variable, and can cumulate with other pressures (land-use change, drought) – resulting in measurable changes in biodiversity, bank erosion, sediment resuspension, or faunal disturbance (Schafft, Engelbart, Hädicke, Schäfer & Wey, 2021; Sexton et al., 2024). The practice of smaller streams and canals also shows that land-based recreational activities in the immediate vicinity of the water (docks, water inlets, riparian areas) can contribute to an increase in turbidity, coliform indicators, and nutrients, especially during high visitor numbers (Cooke & Xia, 2020). In managed systems with monitoring, these impacts can be prevented and kept below significance thresholds (Butler, Pearson & Birtles, 2021). For the canal as a linear infrastructure, this supports the "hotspot-oriented management" approach, in which measures and monitoring are preventively concentrated in a few of the most loaded nodes instead of area-wide interventions.

Mechanisms of ecological resilience: the role of the littoral, hydrology and user behaviour

The observed absence of hypoxia and massive cyanobacterial development in the summer season suggests that the trophic regime is currently stable. Littoral reed (*Ph. australis*) and cattail (*T. latifolia*) belts support biofiltration, sedimentation of fine particles and nutrient retention, thereby reducing the likelihood of short-term eutrophic episodes. In slow-flowing sections, microbial oxidation-reduction processes are applied, which stabilise the organic load (reflected in COD_{Cr}). Pro-environmental behaviour of users also plays an important role: our questionnaires confirmed a high level of responsible behaviour and acceptance of regulatory measures, which the literature identifies as a key "soft" tool with a rapid effect on water quality (Butler et al., 2021). From the perspective of landscape and architectural design, "semi-permeable" shore edges, floating vegetation elements, and mosaic littorals appear to be functional, which simultaneously increase the aesthetic quality of the embankment and reduce hydraulic wave peaks; such solutions also increase social acceptance of regulations (Machar, 2013; Jiang et al., 2025).

Where problems can arise: threshold phenomena and "hotspots"

Reviews show that even with moderate navigation, local hotspots can arise in certain contexts: bank erosion and resuspension of sediment from waves and propellers (wake and prop wash), increased turbidity and phosphorus in shallow bays, disturbance of fish and waterfowl, and transfer of non-native species (Venohr et al., 2018; Schafft et al., 2021). These phenomena did not manifest themselves to a measurable extent in the Bata Canal, but they can accumulate during the confluence of low flows, high temperatures, and weekend

peaks. For these situations, the literature recommends operational measures: temporary speed limits, restrictions on sharp manoeuvres in narrow sections, controlled avoidance of zones with loose sediments, and clear tracking of ship movements in berths (Cooke & Xia, 2020; Butler et al., 2021). Additionally, it is advisable to set "trigger points" for management (e.g. a combination of low flow, water temperature above 24–26°C, and visitor peaks), after which local speed restrictions or traffic redirection are automatically activated.

Evidence-based management: what to add to canal practice

Based on the studies mentioned, the implication framework for the management of the Bata Canal can be expanded to include a comprehensive approach based on adaptive management principles. A key tool is integrated monitoring of water quality and recreational use, which should combine regular sampling campaigns throughout the season (spring–summer–late summer) with continuous logging of temperature and dissolved oxygen concentration. During peak tourist periods, it is appropriate to conduct rapid screenings of turbidity and indicators of faecal pollution in the most visited sections, while in the docks, short-term increases in COD_{Cr} and P_{tot} values should be monitored after large public events (Cooke & Xia, 2020; Butler et al., 2021). Management should also include zoning and capacity regulation, i.e. the definition of quiet zones and sections with speed restrictions in ecologically sensitive parts of the canal, such as littorals with bird nesting or shallow, muddy banks prone to erosion. Soft capacity limits can be applied in selected berths during the busiest periods of the season to avoid excessive load and environmental degradation (Schafft et al., 2021). Prevention of erosion and sediment resuspension is also an important element. These measures include technical and organisational interventions, such as guiding navigation routes through the middle of the profile in shallow sections, reducing waves at sensitive banks, stabilising water entrances and platforms, or restoring littoral vegetation that naturally dampens the hydrodynamic effects of ship traffic (Venohr et al., 2018). No less important is the issue of biosecurity and berth management. It includes the introduction of standards for rinsing vessels and equipment to limit the spread of invasive species, ensuring adequate waste and sanitation infrastructure, and the creation of a user code with an emphasis on zero wastewater discharge and the use of biodegradable cleaning agents. Such a system of supporting measures can significantly contribute to the sustainability of the aquatic environment of the Bata Canal while encouraging environmentally friendly behaviour among its users (Cooke & Xia, 2020; Butler et al., 2021).

Placing the results in the European context

The Bata Canal can be seen as a model of managed linear water infrastructure: at the current intensity of recreation and the application of targeted management, it achieves a balance between recreational and ecological functions. At the same time, the warning from meta-analyses applies that long-term and spatially cumulative effects of recreation may be underestimated if monitoring and management in "hotspots" are missing (Venohr et al., 2018; Schafft et al., 2021). Therefore, we recommend adhering to the principle of adaptive management with clear triggers for temporary restrictions (drought, hot episodes, extreme visitor numbers). On a European scale, the Bata Canal can be understood as a "living lab" for blue-green cultural heritage corridors, where combinations of spatial design, operating rules and community education are tested and their impact on water quality and user comfort.

CONCLUSIONS

Monitored indicators (COD_{Cr}, NO_3^- N, P_{tot}, pH, EC, DO) confirmed the stable water quality of the Bata Canal corresponding to Class II. A slight increase in COD_{Cr} and P_{tot} in Veselí nad Moravou is likely associated with local hydrology and tributary inflows rather than the intensity of recreational boating. Ecological stability is supported by self-purification processes and littoral vegetation, while responsible user behaviour reduces

the likelihood of local pollution "hotspots" in marinas. Potential threshold risks may occur during periods of low flows, heat, and peak visitor numbers; therefore, adaptive management supported by regular monitoring and targeted measures (zoning, speed regulation, control of nutrient inputs, and strengthening of waste and sanitation infrastructure) is recommended. The main limitations of this study include the seasonal sampling period and the focus on physico-chemical indicators; multi-year monitoring incorporating biological parameters and sediment analyses should be considered in future research. Overall, the Bata Canal currently represents a successful example of the coexistence of recreational navigation and aquatic ecosystem protection, with water quality remaining stable under current use intensity due to natural self-purification capacity, littoral vegetation, and user responsibility, while long-term sustainability will rely on proactive, evidence-based management.

Authors' contributions

Conceptualisation: V.H; methodology: V.H.; validation: V.H. and M.F.; formal analysis: V.H.; investigation: V.H. and M.F.; resources: M.F.; data curation: M.F.; writing – original draft preparation: V.H.; writing – review and editing: V.H.; visualisation: V.H.; supervision: V.H.

All authors have read and agreed to the published version of the manuscript.

REFERENCES

Afentou, N., Moore, P., Hull, K., Shepherd, J., Elliott, S. & Frew, E. (2022). Inland Waterways and Population Health and Wellbeing: A Cross-Sectional Study of Waterway Users in the UK. *International Journal of Environmental Research and Public Health*, *19* (21), 13809. https://doi.org/10.3390/ijerph192113809

Arif, M., Behzad, H. M., Tahir, M. & Changxiao, L. (2022). Nature-based tourism influences ecosystem functioning along waterways: Implications for conservation and management. *Science of the Total Environment*, *842*, 156935. https://doi.org/10.1016/j.scitotenv.2022.156935

Butler, B., Pearson, R. G. & Birtles, R. A. (2021). Water-quality and ecosystem impacts of recreation in streams: Monitoring and management. *Environmental Challenges*, *5*, 100328. https://doi.org/10.1016/j.envc.2021.100328

Calderón-Rivera, N., Bartusevičienė, I. & Ballini, F. (2024a). Sustainable development of inland waterways transport: a review. *Journal of Shipping and Trade*, *9* (1), 3. https://doi.org/10.1186/s41072-023-00162-9

Calderón-Rivera, N., Bartusevičienė, I. & Ballini, F. (2024b). Barriers and solutions for sustainable development of inland waterway transport: A literature review. *Transport Economics and Management*, *2*, 31-44.

Cooke, M. T. & Xia, L. (2020). Impacts of land-based recreation on water quality. *Natural Areas Journal*, *40* (2), 179–188. https://doi.org/10.3375/043.040.0208

Czech Standardization Agency [ČAS]. (1993a). *Water quality – Determination of dissolved oxygen – Electrochemical probe method* (CSN EN 25814). Prague: Czech Office for Standards, Metrology and Testing.

Czech Standardization Agency [ČAS]. (1993b). *Water quality – Determination of electrical conductivity* (CSN EN 27888). Prague: Czech Office for Standards, Metrology and Testing.

Czech Standardization Agency [ČAS]. (1996). *Water quality – Determination of the chemical oxygen demand* (CSN ISO 6060). Prague: Czech Office for Standards, Metrology and Testing.

Czech Standardization Agency [ČAS]. (1997). *Water quality – Determination of nitrite and nitrate nitrogen and the sum of both by flow analysis (CFA and FIA) and spectrometric detection* (CSN EN ISO 13395). Prague: Czech Office for Standards, Metrology and Testing.

Czech Standardization Agency [ČAS]. (2004). *Water quality – Determination of phosphorus – Spectrometric method using ammonium molybdate* (CSN EN ISO 6878). Prague: Czech Office for Standards, Metrology and Testing.

Czech Standardization Agency [ČAS]. (2012a). *Water quality – Determination of pH* (CSN EN ISO 10523). Prague: Czech Office for Standards, Metrology and Testing.

Czech Standardization Agency [ČAS]. (2012b). *Water quality – Determination of dissolved oxygen – Electrochemical probe method* (CSN EN ISO 5814). Prague: Czech Office for Standards, Metrology and Testing.

Czech Standardization Agency [ČAS]. (2017). *Water quality – classification of surface water quality* (CSN 75 7221). Prague: Czech Office for Standards, Metrology and Testing.

Jiang, X., Li, X., Wang, M., Zhang, X., Zhang, W., Li, Y., Cong, X. & Zhang, Q. (2025). Multidimensional visual preferences and sustainable management of heritage canal waterfront landscape based on panoramic image interpretation. *Land*, *14* (2), 220. https://doi.org/10.3390/land14020220

Machar, I. (2013). The effect of landscape character change on the recreation function of a water management construction in the landscape. Case study: Bata Canal, South Moravia (Czech Republic). In *Public recreation and landscape protection – with man hand in hand* (pp. 190–195). Mendel University Press.

Mako, P. & Galieriková, A. (2021). Inland navigation on the Danube and the Rhine waterways. *Transportation Research Procedia*, *55*, 10–17. https://doi.org/10.1016/j.trpro.2021.06.002

Némethy, S. A., Ternell, A., Bornmalm, L., Lagerqvist, B. & Szemethy, L. (2022). Environmental viability analysis of connected European inland–marine waterways and their services in view of climate change. *Atmosphere*, *13* (6), 951. https://doi.org/10.3390/atmos13060951

Sexton, A. N., Beisel, J. N., Staentzel, C., Wolter, C., Tales, E., Belliard, J., ... & Jeliazkov, A. (2024). Inland navigation and land use interact to impact European freshwater biodiversity. *Nature Ecology & Evolution*, *8* (6), 1098–1108. https://doi.org/10.1038/s41559-024-02306-8

Schafft, M., Wegner, B., Meyer, N., Wolter, C. & Arlinghaus, R. (2021). Ecological impacts of water-based recreational activities on freshwater ecosystems: A global meta-analysis. *Proceedings of the Royal Society B*, *288* (1959), 20211623. https://doi.org/10.1098/rspb.2021.1623

Steege, V., Engelbart, D., Hädicke, N. T., Schäfer, K. & Wey, J. K. (2022). Germany's federal waterways – A linear infrastructure network for nature and transport. *Nature Conservation*, *47*, 15–33. https://doi.org/10.3897/natureconservation.47.90217

Venohr, M., Langhans, S. D., Peters, O., Hölker, F., Arlinghaus, R., Mitchell, L. & Wolter, C. (2018). The underestimated dynamics and impacts of water-based recreational activities on freshwater ecosystems. *Environmental Reviews*, *26* (2), 199–213. https://doi.org/10.1139/er-2017-0083

WPŁYW ŻEGLUGI REKREACYJNEJ NA JAKOŚĆ WODY I EKOSYSTEMY KANAŁU BATA

STRESZCZENIE

Celem badania była ocena wpływu ruchu łodzi rekreacyjnych na jakość wody i stan ekologiczny kanału Bata (Czechy), ważnego szlaku turystycznego na Morawach Południowych. Przeprowadzono pomiary terenowe parametrów fizykochemicznych wody ($ChZT_{Cr,}$ NO_3^- N, P_{tot}, pH, przewodność, tlen rozpuszczony) oraz ankietę na miejscu wśród użytkowników kanału. Wyniki wykazały, że ruch łodzi rekreacyjnych nie powoduje mierzalnego pogorszenia jakości wody, nawet na najbardziej intensywnie użytkowanych odcinkach. Największe wartości $ChZT_{Cr}$ (do 23,4 $mg \cdot l^{-1}$) i P_{tot} (0,2 $mg \cdot l^{-1}$) odnotowano w miejscowości Veselí nad Moravou, podczas gdy wszystkie wartości pozostawały poniżej progów wytycznych czeskich dla wód powierzchniowych. Wyniki podkreślają znaczenie naturalnych procesów samooczyszczania, warunków hydrologicznych oraz odpowiedzialnego zachowania odwiedzających dla utrzymania wysokiej jakości wód. Z perspektywy planowania krajobrazu badanie wskazuje na kluczową rolę zróżnicowania stref funkcjonalnych, właściwego zarządzania linią brzegową i dostosowanych reżimów operacyjnych jako elementów błękitno-zielonej infrastruktury wzmacniającej stabilność ekologiczną. Kanał Bata stanowi udany przykład harmonijnego współistnienia rekreacji i ochrony ekosystemów wodnych. Pokazuje, że przy obecnym poziomie użytkowania rekreacyjnego dobre warunki ekologiczne można utrzymać dzięki odpowiedniemu zarządzaniu oraz wysokiej świadomości użytkowników.

Słowa kluczowe: kanał Bata, żeglarstwo rekreacyjne, jakość wody, eutrofizacja, zarządzanie środowiskiem, planowanie krajobrazu, błękitno-zielona infrastruktura

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SEASONAL VEGETATION CHANGES ON A SELECTED SECTION OF A RAILWAY LINE IN THE SOUTH MORAVIAN REGION (CZECH REPUBLIC) – A CASE STUDY

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ABSTRACT

Railways constitute a pivotal component of linear transport infrastructure. The monitored section is part of the line connecting Vienna and Kraków, the construction of which began in 1837. The objective of the study was to assess the species composition of vegetation in a designated section of the railway. The evaluation was executed through the implementation of the phytocoenological relevé method, with the assessment conducted in the year 2021, during the months of April, June, August, and October. During the monitoring process, a total of 31 plant species present within the trackbed of the designated section were documented. The results indicate that the section under observation is distinguished by relatively abundant and species-diverse vegetation, the composition and coverage of which undergoes changes during the vegetation period. The impact of vegetation on the structural stability of railway lines is a matter of concern, as it can also adversely affect the fluidity and safety of rail transport. Consequently, the regular monitoring and evaluation of vegetation should be an integral part of the operational maintenance of railway infrastructure.

Keywords: plant, diversity of plant species, anthropogenic area, anthropogenic vegetation, railway

INTRODUCTION

Railways constitute a linear transport infrastructure that exhibits a number of common habitat characteristics, irrespective of geographical area or climate zone. These habitats are entirely of anthropogenic origin, involving the removal of original vegetation and the preparation of a new substrate for the construction of embankments and the laying of rails (Borda-de-Água, Ascensão, Sapage, Barrientos & Pereira, 2017; Borda-de-Água et al., 2019). The linear habitats thus created are characterised by extreme environmental conditions, including dry, rocky, and sun-exposed substrates with often high levels of pollution, especially heavy metals (Wiłkomirski, Galera, Sudnik-Wójcikowska, Staszewski & Malawska, 2012). These stress factors have been identified as a primary cause of the decline in biodiversity, particularly among plant species (Kalusová et al., 2017).

Transport infrastructure, including railways, also significantly contributes to the spread of plant diasporas to new areas (von der Lippe & Kowarik, 2008; Winkler et al., 2024). Railway corridors frequently serve as conduits for the migration of flora, thereby facilitating the traversal of natural and ecological barriers (Rashid et al., 2021). In the past, several species, e.g. *Geranium purpureum*, have spread to new regions across Europe thanks to railway transport and subsequently colonised other urban habitats (Büscher, Keil & Loos, 2008; Eliáš, 2011).

Furthermore, railway environments are characterised by the presence of diverse microhabitats, which are conducive to the proliferation of species with divergent ecological requirements. Rocky and exposed

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surfaces tend to be inhabited by xerophilic and thermophilic species, while mesophilic and hygrophilic species thrive in shady and wetter microdepressions with less permeable surfaces (Wittig & Lienenbecker, 2003; Fornal-Pieniak & Wysocki, 2011).

Railways have been demonstrated to have a substantial impact on the environment, manifesting in two principal ways. Firstly, the construction phase involves a notable disruption to the existing topography, a consequence that is subsequently compounded by the operational and maintenance demands of the railway infrastructure. The processes by which plant communities are re-formed after disturbance have been a long-standing topic of ecological research (Götzenberger et al., 2012). Nature conservation must move beyond the traditional notions of wild and cultivated nature (Kueffer & Kaiser-Bunbury, 2014) and embrace new hybrid approaches to protect biotopes that exhibit biological diversity, many of which have been shaped by human civilisation (Burney & Burney, 2007; Winkler et al., 2021). Respect for spontaneous vegetation can support biodiversity in urban environments (Reif & Kreß, 2014).

Each phase of railway construction and operation has a substantial impact on the proliferation of vegetation. Furthermore, plant communities in railway areas are exposed to constant disturbance pressure due to the intensive transport of people and goods, as well as management interventions (e.g. mowing or herbicide application) aimed at suppressing unwanted vegetation (Rutkovska, Pučka, Evarts-Bundersanta & Paidere, 2013).

Disturbed railway habitats can serve as sites for the propagation of plant material originating from various local and regional sources. These species then interact ecologically, adapt to the new environment, and can affect the biodiversity of the entire area (Rutkovska et al., 2013). As railway networks traverse a variety of landscape uses, ranging from agricultural and urban areas to sites of high ecological value or intact forests, they facilitate the propagation of non-native species, even into relatively pristine habitats. This phenomenon has the potential to disrupt the species composition of surrounding ecosystems, particularly adjacent communities (Hansen & Clevenger, 2005; Fornal-Pieniak & Wysocki, 2010).

In the Czech Republic, the railway infrastructure is characterised by a network configuration that encompasses an area of approximately 30,128 ha. A total of 9,566 km of operational railway tracks have been constructed, with the cumulative length of all railway tracks reaching 15,570 km (Krejčíříková, 2017).

The segment of the railway that is under observation is part of the line from Vienna to Kraków, the construction of which commenced in 1837. The railway was known as the Northern Railway of Emperor Ferdinand. The inaugural test run occurred on 15 April 1841, in the segment designated Břeclav–Staré Město u Uherské Hradiště, with the official opening of the line to traffic occurring on 5 May of the same year. The town of Rohatec was not established until 1866. In 1872, the Northern Railway underwent an expansion that included the addition of double tracking. Beginning in 1907, the utilisation of trains for the transportation of mail has also been documented. In 1934, a new five-kilometre line was constructed from Ratíškovice to Rohatec. This line was used to transport lignite from the recently opened Tomáš (later Theodor) mine. During World War II, significant destruction occurred, particularly on 10 April 1945, when the railway bridge in Rohatec towards Sudoměřice was destroyed. In the aftermath of the war, the railway line was reinstated, and in 1948, a new arch bridge was constructed (Bíza & Skácel, 1973).

Between 1960 and 1965, a new railway stop was constructed in Rohatec, and the route of the Rohatec––Kolonie station underwent expansion, facilitating the passage of trains transporting lignite from Ratíškovice to Hodonín. In 1973, the Břeclav–Otrokovice rail line experienced the passage of approximately 20 passenger trains and 4 express trains on a daily basis. From 1995 to 1998, the line underwent a comprehensive reconstruction, during which the tracks were replaced, and the signalling equipment was modernised. Presently, switching operations are managed automatically (Bíza, 2012).

A fundamental ecological consequence of railways is a set of changes that occur in the adjacent natural vegetation (Wang, Gillespie, Liang, Mushkin & Wu, 2015; Pollock, Nielsen & St. Clair, 2017).

The aim of the work was (i) to evaluate the species composition of vegetation in a selected section of the railway, (ii) to monitor changes in vegetation composition during the growing season, and (iii) to evaluate potential interactions between vegetation and railway operations.

MATERIAL AND METHODS

Characteristics of the study area

The selected section of the railway line is located in the cadaster of the municipality of Rohatec in the South Moravian Region, at an average altitude of approximately 185 m above sea level. The territory falls within the Pannonian province and the Intracarpathian Depression system, specifically into the Lower Moravian Valley unit and the Dyje-Moravian Alley sub-unit. The bedrock is composed of Neogene sediments, primarily calcareous clays with a mixture of silty and sandy components. These sediments are slightly impermeable to impermeable. Rohatec is located on the periphery of the Moravian Sahara, a geographical region characterised by the presence of sand dunes and blown sands. The landscape around the Morava River was shaped by alluviums of gravel, sand, and loess, with a maximum thickness of 18 m in certain areas. The territory is part of the Morava River basin, which in the past experienced unregulated fluvial activity, resulting in the formation of numerous meanders and side branches. The most prevalent rock formations are loess and loamy sands, which are characterised by a preponderance of fine quartz grains. According to the climatic regionalisation, the area is classified as a warm and dry climatic zone, characterised by protracted hot summers and brief, mild winters. The spring and autumn seasons are marked by short and warm periods, respectively. Spring frosts are a common occurrence in the lowlands surrounding the river. The average annual temperature is 9.5–9.7°C, with July being the warmest month, reaching 19.8°C. The annual precipitation in this region is approximately 585–600 mm, and the predominant wind directions are from the southeast and northwest (Culek et al., 1996; Czech Geological Survey [CGS], 2017; CGS, 2018). Figure 1 shows the location of the study railway line (GPS 48.8914683N, 17.1950708E).

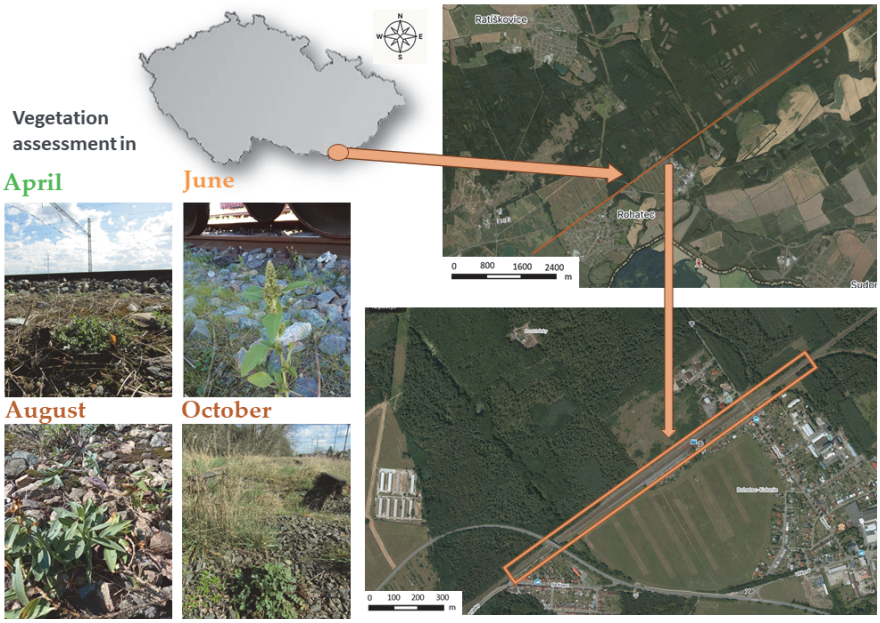


Fig. 1. Map of the railway line and the monitored periods

Source: own work.

Vegetation assessment methodology

The vegetation assessment was executed through the implementation of the phytocoenological relevé method (Westhoff & van der Maarel, 1978). These phytocoenological relevés were captured within the right-of-way of a designated railway segment. A total of 10 relevés were recorded, each measuring 2 × 2 m (i.e. 4 m²). The assessment was conducted on four occasions during 2021, with the same areas surveyed on each occasion. The initial procedure was conducted in April, the subsequent procedure in June, the third procedure in August, and the final procedure in October. The extent of coverage for individual species was determined through direct estimation in percentages. The nomenclature of plant species was derived from the Pladias database (Pladias, 2021).

Statistical analysis

The relationships between individual assessment dates and the coverage of the identified plant species were evaluated using multivariate analyses of ecological data. First, a segmental analysis detrended correspondence analysis (DCA) was performed, in which the length of the gradient was determined. Subsequently, the influence of the management method on vegetation was tested using redundancy analysis (RDA). The statistical significance of the results was verified by a Monte Carlo test with 999 permutations. The Canoco 5.0 program (Braak & Šmilauer, 2012) was used for all calculations.

RESULTS AND DISCUSSION

During the assessment, a total of 31 plant species were recorded as occurring in the trackbed of the selected railway section. Table 1 provides an overview of the plant species found, as well as an overview of floristic regions and elevational belts. As illustrated in Figure 2, the representation of individual species is contingent upon the total coverage, while Figure 3 demonstrates the proportion of biological plant groups in individual assessment dates.

Table 1. Overview of found plant species and an overview of their floristic areas and altitudinal zones in the Czech Republic

Species	Abbreviation	Biological groups	Floristic region	Elevational belt in the Czech Republic
Anagallis arvensis	*AnaArve*	annual dicotyledons	circumpolar	lowlands, colline belt (submontane belt)
Amaranthus retroflexus	*AmaRetr*	annual dicotyledons	Western America	lowlands, colline belt (submontane belt)
Arrhenatherum elatius	*ArrElat*	perennial monocotyledons	Europe	lowlands, colline belt, submontane belt, montane belt
Bromus inermis	*BroIner*	perennial monocotyledons	circumpolar	lowlands, colline belt (subalpine belt)
Bromus tectorum	*BroTect*	annual monocotyledons	Europe, Western Asia	lowlands, colline belt (submontane belt)
Calamagrostis epigejos	*CalEpig*	perennial monocotyledons	Europe, Asia	lowlands, colline belt, submontane belt, montane belt
Capsella bursa-pastoris	*CapBurs*	annual dicotyledons	circumpolar	lowlands, colline belt, submontane belt, montane belt
Centaurea jacea	*CenJace*	perennial dicotyledons	Europe	lowlands, colline belt, submontane belt
Centaurea stoebe	*CenStoe*	perennial dicotyledons	Europe	lowlands, colline belt, submontane belt
Convolvulus arvensis	*ConArve*	perennial dicotyledons	Europe, Asia, circumpolar	lowlands, colline belt, submontane belt
Digitaria sanguinalis	*DigSang*	annual monocotyledons	Asia, Africa, circumpolar	lowlands, colline belt (submontane belt)
Echium vulgare	*EchVulg*	perennial dicotyledons	Europe, Western Asia	lowlands, colline belt, submontane belt
Elymus hispidus	*ElyHisp*	perennial monocotyledons	Europe, Western Asia	lowlands, colline belt (submontane belt)
Epilobium adenocaulon	*EpiAden*	perennial dicotyledons	Europe, Asia, Americas	lowlands, colline belt, submontane belt, montane belt, subalpine belt

Table 1 (cont.)

Species	Abbreviation	Biological groups	Floristic region	Elevational belt in the Czech Republic
Erodium cicutarium	*EroCicu*	perennial dicotyledons	Europe, Western Asia, circumpolar	lowlands, colline belt, submontane belt
Geranium robertianum	*GerRobe*	annual dicotyledons	Europe, Asia	lowlands, colline belt, submontane belt, montane belt
Chenopodium album	*CheAlbu*	annual dicotyledons	circumpolar	lowlands, colline belt, submontane belt, montane belt
Leontodon hispidus	*LeoHisp*	perennial dicotyledons	Europe	lowlands, colline belt, submontane belt, montane belt, subalpine belt
Medicago falcata	*MedFalc*	perennial dicotyledons	Europe, Asia	lowlands, colline belt, submontane belt
Melica transsilvanica	*MelTran*	perennial monocotyledons	Europe	lowlands, colline belt
Panicum miliaceum	*PanMili*	annual monocotyledons	Asia	without information
Portulaca oleracea	*PorOler*	annual dicotyledons	circumpolar	lowlands, colline belt (submontane belt)
Potentilla argentea	*PotArge*	perennial dicotyledons	Europe, Western Asia	lowlands, colline belt, submontane belt, montane belt
Rubus sp.	*RubSp.*	perennial dicotyledons	Europe, Caucasus, Eastern America	without information
Rumex thyrsiflorus	*RumThyr*	perennial dicotyledons	Europe, Asia	lowlands, colline belt
Saponaria officinalis	*SapOffi*	perennial dicotyledons	Europe, Western Siberia	lowlands, colline belt, submontane belt
Senecio viscosus	*SenVisc*	annual dicotyledons	Europe	lowlands, colline belt, submontane belt, montane belt
Stellaria media	*SteMedi*	annual dicotyledons	circumpolar	lowlands, colline belt, submontane belt
Trifolium arvense	*TriArve*	annual dicotyledons	Europe, Western Siberia	lowlands, colline belt, submontane belt
Trifolium repens	*TriRepe*	perennial dicotyledons	circumpolar	lowlands, colline belt, submontane belt, montane belt, subalpine belt
Urtica dioica	*UrtDioi*	perennial dicotyledons	circumpolar	lowlands, colline belt, submontane belt, montane belt
Vicia sepium	*VicSepi*	annual dicotyledons	Europe, Western Siberia	lowlands, colline belt, submontane belt, montane belt, subalpine belt

Source: own work according to floristic regionalisation by Klotz, Kühn and Durka (2002).

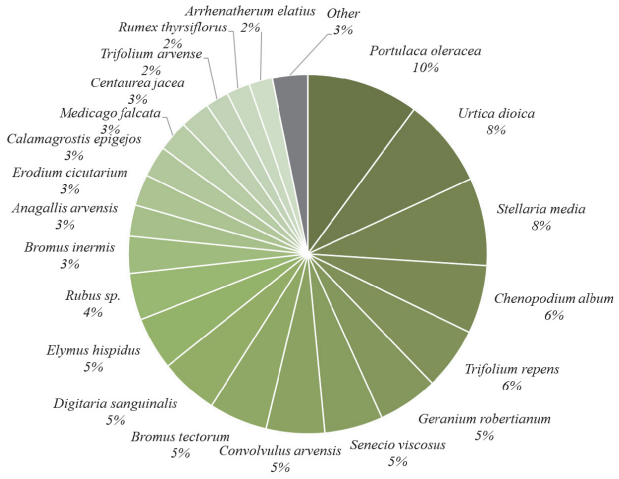


Fig. 2. Representation of plant species found in the trackbed of the monitored railway section

Source: own work.

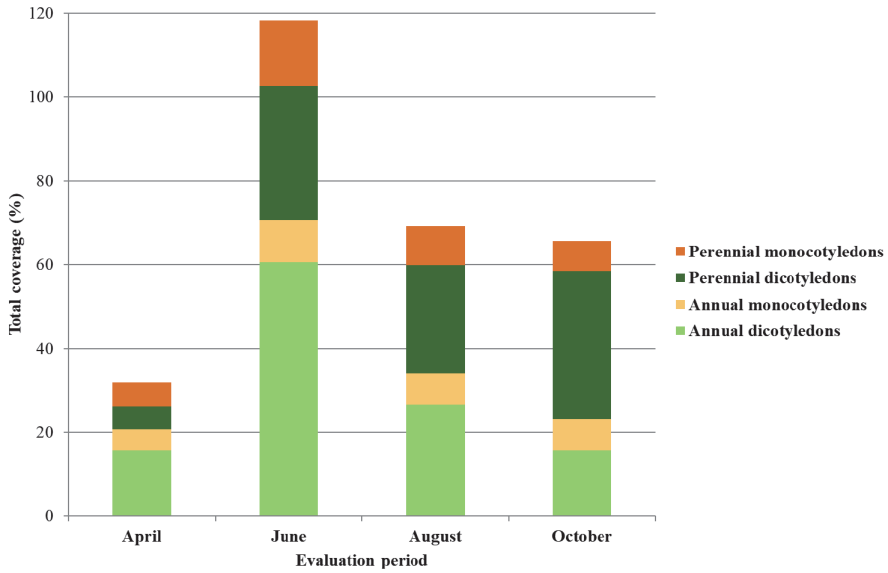


Fig. 3. Contributions of biological groups to vegetation cover in assessment terms

Source: own work.

RDA analysis defines the spatial arrangement of individual plant species and the evaluation term. The results of the RDA analysis are significant at the significance level of $\alpha = 0.04$. The results are therefore statistically highly significant. According to the ordination diagram (Fig. 4), the plant species can be divided into four groups.

The first group of species had a more significant coverage in April and was the species *Epilobium adenocaulon* (*EpiAden*).

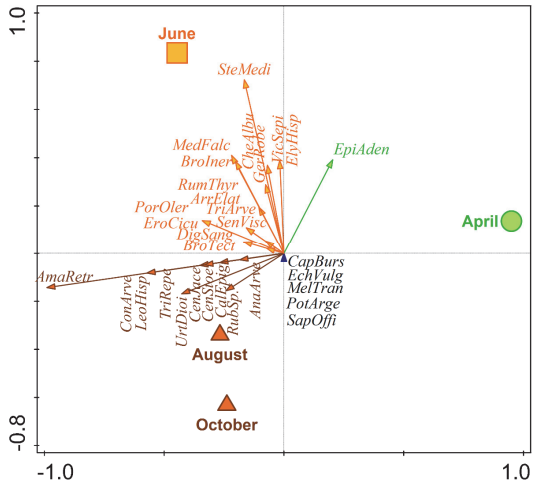


Fig. 4. Ordination diagram expressing the relationship between the found plant species and the terms evaluated on the trackbed of the selected railway section (RDA analysis results; pseudo $F = 0.5$; $p = 0.04$)

Source: own work.

The second group had more significant coverage in June: *Arrhenatherum elatius* (*ArrElat*), *Bromus inermis* (*BroIner*), *Bromus tectorum* (*BroTect*), *Digitaria sanguinalis* (*DigSang*), *Elymus hispidus* (*ElyHisp*), *Erodium cicutarium* (*EroCicu*), *Geranium robertianum* (*GerRobe*), *Chenopodium album* (*CheAlbu*), *Medicago falcata* (*MedFalc*), *Portulaca oleracea* (*PorOler*), *Rumex thyrsiflorus* (*RumThyr*), *Senecio viscosus* (*SenVisc*), *Stellaria media* (*SteMedi*), *Trifolium arvense* (*TriArve*), *Vicia sepium* (*VicSepi*).

The third group had more significant coverage in August and October: *Amaranthus retroflexus* (*AmaRetr*), *Anagallis arvensis* (*AnaArve*), *Calamagrostis epigejos* (*CalEpig*), *Centaurea jacea* (*CenJace*), *Centaurea stoebe* (*CenStoe*), *Convolvulus arvensis* (*ConArve*), *Leontodon hispidus* (*LeoHisp*), *Rubus* sp. (*Rub*Sp.), *Trifolium repens* (*TriRepe*), *Urtica dioica* (*UrtDioi*).

The fourth group consists of species that were more influenced by factors other than the assessment date. These are the species: *Capsella bursa-pastoris* (*CapBurs*), *Echium vulgare* (*EchVulg*), *Melica transsilvanica* (*MelTran*), *Potentilla argentea* (*PotArge*), *Saponaria officinalis* (*SapOffi*).

Habitats created by human civilisation represent a significant component of the Central European landscape (Lososová et al., 2006). These habitats also include transport infrastructure, which significantly changes environmental conditions and landscape character (Wiłkomirski et al., 2012). The upper portion of the railway track is composed of a system of transversely laid sleepers that support the rails. These elements are then placed in a gravel bed, where they coalesce to form the frame structure of the track. The lower portion of the railway track is engineered to ensure its stability and to transmit the static and dynamic pressures that are generated by the movement of trains. The embankment of the track is composed of a material whose properties must ensure stability and long-term load-bearing capacity. Non-cohesive soils are the most suitable, as they are characterised by their ability to retain their physical properties despite climatic variations, such as freezing during winter months, and they exhibit higher load-bearing capacity than cohesive soils (Plášek, Zvěřina, Svoboda & Mockovčiak, 2004).

The section of railway that is subject to monitoring and observation therefore constitutes an environment that has been altered through anthropogenic influence, exhibiting substantial disparities when compared with the adjacent natural habitats. The aforementioned conditions exert a profound influence on the composition and structure of vegetation. Only species that possess the capacity to withstand extreme temperatures, drought, and mechanical disturbance will prevail within the designated area. The site is situated in the warmest region of the Czech Republic, where the onset of spring is rapid, summers are hot and dry with low rainfall, and autumns are warm. Consequently, there is extreme overheating of stony and sandy subsoils, the surface temperature of which often exceeds 50°C. In the context of such habitats, heliophytes – that is, species that demonstrate a preference for sunny and dry environments – are dominant. The low overall vegetation coverage is related to the structure of the gravel bed, which consists of coarse crushed aggregate with a thickness of over 0.3 m. The species *Rubus* sp. has a powerful root system, capable of drawing water from greater depths. Due to its dense growth, this species poses a significant challenge in terms of removal, as it can threaten the stability and structural integrity of the railway track base.

Portulaca oleracea is a low, prostrate plant with fleshy leaves, found in abundance on sandy soils, wastelands, and roadsides (Pladias, 2022). It has been observed to establish itself on the railway superstructure, where its biomass accumulates. Bromus tectorum is an annual herb that propagates through seeds and is frequently observed in anthropogenically influenced habitats and sandy soils (Pladias, 2022). This species presents a challenge in the context of railway superstructure.

The development of railways and the associated transportation infrastructure has contributed to the dissemination of non-native and exotic plant species (Galera et al., 2011). Herbicide-resistant species include *Equisetum arvense*, *Galium* spp., and *Conyza canadensis* (Torsterson, 2001). Railway sites are home to native and introduced ruderal species, which occur not only in railway yards but also on embankments, sidings, and turntables. These sites function as ecological corridors for plants with specific environmental requirements (Galera, Sudnik-Wójcikowska, Wierzbicka & Wiłkomirski, 2011).

The species recorded in this study were *Amaranthus retroflexus*, *Digitaria sanguinalis*, *Calamagrostis epigejos*, and *Epilobium adenocaulon*.

Regression tree analysis identified two main factors influencing the species richness of vascular plants – average annual temperature and the number of freight trains. The richness of native species was higher in sites with temperatures below 8.65°C, while non-native species were more numerous in areas with intensive freight transport (> 7,640 trains). Higher transport volume also positively affected the richness of archaeophytes and neophytes (threshold values of 2,524 and 7,640 trains). Red Book species were more common at warmer sites (> 9.04°C). In terms of life forms, the richness of therophytes increased with temperature, while hemicryptophytes and chamaephytes were more abundant in colder areas (Májeková et al., 2025). In our study, the endangered species *Melica transsilvanica* was recorded.

There are many reasons why it is necessary to limit the growth of vegetation on railways and thereby ensure the safety of railway transport. The main objective is to maintain the quality and stability of the railway track. Vegetation control contributes to the stability of the ballast bed, the protection of wooden sleepers, the safety of employees and the prevention of fires caused by dry vegetation (Torstensson, 2001).

If the gravel bed is not cleaned regularly, weed residues and organic material can fill its cavities, which worsens drainage. In winter, freezing water can cause the track to shift or deform. Vegetation on the tracks also increases the risk of wheel skidding, lengthens braking distances and thus endangers traffic safety. The properties of herbicides used on railways can vary depending on the composition of the soil. In soils with a higher content of clay and organic matter, they adsorb, which reduces microbial activity and slows down decomposition, thereby increasing the persistence of herbicides in the environment (Torstensson, 2001).

Another issue is the clogging of drainage systems by vegetation, which leads to water retention and can cause the collapse of embankments or railway banks (Hutniczak, Urbisz, Urbisz & Strzeleczek, 2022).

Vegetation growth is further influenced by the annual distribution of precipitation. The monitored area is characterised by dry and hot summers with uneven precipitation. The greatest vegetation growth occurs in spring and early summer (April–June), when precipitation is more frequent. On the contrary, in late summer and autumn (August–October), plants do not grow or dry out, which leads to the accumulation of dry biomass. This can negatively affect the braking distance of train sets and traffic safety. For these reasons, vegetation regulation in railway yards is necessary not only to maintain the quality of the infrastructure, but above all to ensure the safe operation of railway transport.

CONCLUSIONS

The results of the study demonstrate that the trackbed of the selected railway section exhibits a relatively rich and diverse vegetation community. In the study of plant ecology, it has been observed that species that demonstrate a preference for sunny locations, as indicated by their extensive root systems or high seed production, are often dominant in such environments. However, the growing roots of these plants have the potential to disrupt the structural integrity of the railway line. The results also demonstrate that the species composition and amount of vegetation undergo changes during the growing season.

From the perspective of vegetation assessment, the most opportune period appears to be June, when the highest levels of biomass production and the greatest species diversity occur. Vegetation has been shown to exert a significant influence on the structural stability of railway tracks. Additionally, its impact on the smoothness and safety of railway transport has been demonstrated. This phenomenon not only poses a potential fire hazard but also exerts an influence on the composition of the surrounding vegetation. Consequently, regular monitoring and assessment of vegetation along railway lines should be a standard component of railway operational maintenance.

Authors' contributions

Conceptualisation: J.W.; methodology: J.W. and A.M.; validation: J.W., M.H. and A.M.; formal analysis: J.W.; investigation: J.W.; resources: J.W. and M.M.; data curation: J.W.; writing – original draft preparation: J.W. and M.H.; writing – review and editing: J.W. and M.H..; visualisation: J.W.; supervision: J.W.; project administration: J.W.; funding acquisition: J.W. and A.M.

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REFERENCES

Bíza, J. & Skácel, J. (1973). *Slovácká obec Rohatec*. Brno: MNV.

Bíza, Z. (2012). Historie Rohatce Kolonie a Soboněk XI. *Rohatecká obec – občanský zpravodaj*, *16* (5), 6–7.

Borda-de-Água, L., Ascensão, F., Sapage, M., Barrientos, R. & Pereira, H. M. (2019). On the identification of mortality hotspots in linear infrastructures. *Basic and Applied Ecology*, *34*, 25–35. https://doi.org/10.1016/j.baae.2018.11.001

Borda-de-Água, L., Barrientos, R., Beja, P. & Pereira, H. M. (2017). *Railway ecology*. Springer Nature.

Braak, C. J. F. & Šmilauer, P. (2012). *Canoco reference manual and user's guide: software for ordination (version 5.0)*. Ithaca: Microcomputer Power.

Burney, D. A. & Burney, L. P. (2007). Paleoecology and "inter-situ" restoration on Kaua'i, Hawai'i. *Frontiers in Ecology and the Environment*, *5* (9), 483–490. https://doi.org/10.1080/01426397.2011.559311

Büscher, D., Keil, P. & Loos, G. (2008). Neue Ausbreitungstendenzen von primär als Eisenbahnwanderer aufgetretenen Pflanzenarten im Ruhrgebiet: Die Beispiele Eragrostis minor, *Geranium purpureum* und *Saxifraga tridactylites*. *Braunschweiger Geobotanische Arbeiten (Braunschweig)*, *9*, 97–106.

Culek, M. (1996). Biogeografické členění České republiky. Praha: Enigma.

Czech Geological Survey [CGS]. (2017). *Map of soil types of the Czech Republic, 1:50000*. Retrieved from: https://mapy.geology.cz/pudy [accessed: 08.11.2024].

Czech Geological Survey [CGS]. (2018). *Geological map of the Czech Republic, 1:50000*. Retrieved from: https://mapy.geology.cz/geocr50/ https://mapy.geology.cz/pudy [accessed: 08.11.2024].

Eliáš, P. (2011). *Geranium purpureum* Vill. – new alien species to the Slovak flora. *Thaiszia – Journal of Botany*, *21* (1–2), 21–28.

Fornal-Pieniak, B. & Wysocki, C. (2010). Flora nasypu nieużytkowanej linii kolejowej w okolicy Sokołowa Podlaskiego. *Woda – Środowisko – Obszary Wiejskie, 10*, *3* (31), 85–94.

Fornal-Pieniak, B. & Wysocki, C. (2011). Vegetation on the railway-line embankment at Tarnów. *Ekológia (Bratislava)*, *30* (4), 414–421. https://doi.org/10.4149/ekol_2011_04_414

Galera, H., Sudnik-Wójcikowska, B., Wierzbicka, M. & Wiłkomirski, B. (2011) Encroachment of forest species into operating and abandoned railway areas in north-eastern Poland. *Plant Biosyst*. *145*, 23–36. https://doi.org/10.1080/11263504.2010.522803

Götzenberger, L., Bello, F. de, Bråthen, K. A., Davison, J., Dubuis, A., Guisan, A., Lepš, J., Lindborg, R., Moora, M., Pärtel, M., Pellissier, L., Pottier, J., Vittoz, P., Zobel, K. & Zobel, M. (2012). Ecological assembly rules in plant communities – Approaches, patterns and prospects. *Biological Reviews*, *87* (1), 111–127. https://doi.org/10.1111/j.1469-185X.2011.00187.x

Hansen, M. J. & Clevenger, A. P. (2005). The influence of disturbance and habitat on the presence of non-native plant species along transport corridors. *Biological Conservation*, *125* (2), 249–259. https://doi.org/10.1016/j.biocon.2005.03.024

Hutniczak, A., Urbisz, A., Urbisz, A. & Strzeleczek, Ł. (2022). Factors Affecting Plant Composition in Abandoned Railway Areas with Particular Emphasis on Forest Proximity. *Diversity*, *14*, 1141. https://doi.org/10.3390/d14121141

Kalusová V., Chytrý M., Kleunen M. van, Mucina L., Dawson W., Essl F., Kreft H., Pergl J., Weigelt P., Winter M. & Pyšek P. (2017). Naturalization of European plants on other continents: The role of donor habitats. *Proceedings of the National Academy of Sciences*, *114* (*52*), *1*3756–13761. https://doi.org/10.1073/pnas.1705487114

Klotz, S., Kühn, I. & Durka, W. (2002). *Angaben zu den Arealen*. In: Klotz S., Kühn I. & W. Durka (Eds), *BIOLFLOR: eine Datenbank mit biologisch-ökologischen Merkmalen zur Flora von Deutschland* (pp. 227–239). Bonn: Bundesanstalt für Vegetationskunde, Naturschutz und Landschaftspflege.

Krejčiříková, H. (2017). *Railway construction 1*. Praha: České vysoké učení technické.

Kueffer, C. & Kaiser-Bunbury, C. N. (2014). Reconciling conflicting perspectives for biodiversity conservation in the Anthropocene. *Frontiers in Ecology and the Environment, 12* (2), 131–137. https://doi.org/10.1890/120201

Lippe, M. von der & Kowarik, I. (2008). Do cities export biodiversity? Traffic as dispersal vector across urban–rural gradients. *Diversity and Distributions*, *14*, 18–25. https://doi.org/10.1111/j.1472-4642.2007.00401.x

Lososová, Z., Chytrý, M., Kühn, I., Hájek, O., Horáková, V., Pyšek, P. & Tichý, L. (2006). Patterns of plant traits in annual vegetation of man-made habitats in central Europe. *Perspectives in Plant Ecology, Evolution and Systematics*, *8* (2), 69–81.

Májeková, J., Čiliak, M., Dudáš, M., Eliáš, P., Hrivnák, R., Svitková, I., Hegedüšová Vantarová K. & Slezák, M. (2025). Climate and traffic volume control plant species richness in railway areas. *Flora*, *330*, 152780. https://doi.org/10.1016/j.flora.2025.152780

Pladias (2025). *Database of the Czech Flora and Vegetation*. Department of Botany and Zoology Faculty of Science Masaryk University, Brno, Czech Republic. Retrieved from: https://pladias.cz/en/ [accessed: 10.01.2025].

Plášek, O., Zvěřina, P., Svoboda, R. & Mockovčiak, M. (2004). Železniční stavby – železniční spodek a svršek. Brno: Akademické nakladatelství CERM.

Pollock, S. Z., Nielsen, S. E. & St. Clair, C. C. (2017). A railway increases the abundance and accelerates the phenology of bear-attracting plants in a forested, mountain park. *Ecosphere*, *8* (10), e01985. https://doi.org/10.1002/ecs2.1985

Rashid, I., Haq, S. M., Lembrechts, J. J., Khuroo, A. A., Pauchard, A. & Dukes, J. S. (2021). Railways redistribute plant species in mountain landscapes. *Journal of Applied Ecology*, *58*, 1967–1980. https://doi.org/10.1111/1365-2664.13961

Reif, J. & Kreß, C. (2014). *Blackbox Gardening – Mit Versamenden Pflanzen Garten Gestalten*. Verlag Eugen Ulmer.

Rutkovska, S., Pučka, I., Evarts-Bundersanta, P. & Paidere, J. (2013). The role of railway lines in the distribution of alien plant species in the territory of Daugavpils City (Latvia). *Estonian Journal of Ecology*, *62*, 212–225. https://doi.org/10.3176/eco.2013.3.03

Torstensson, L. (2001). Use of herbicides on railway tracks in Sweden. *Pesticide Outlook, 12* (1), 16–21.

Wang, G., Gillespie, A. R., Liang, S., Mushkin, A. & Wu, Q. (2015). Effect of the Qinghai-Tibet Railway on vegetation abundance. *International Journal of Remote Sensing*, *36 (*19–20), 5222–5238. https://doi.org/10.1080/01431161.2015.1041179

Westhoff, V., Maarel, E. van der (1978). *The Braun-Blanquet approach*. In R.H. Whittaker (Ed.), *Classification of Plant Communities* (pp. 289–399). Hague: W. Junk.

Wiłkomirski, B., Galera, H., Sudnik-Wójcikowska, B., Staszewski, T. & Malawska, M. (2012). Railway tracks-habitat conditions, contamination, floristic settlement – A review. *Environment and Natural Resources Research*, *2* (1), 86. https://doi.org/10.5539/enrr.v2n1p86

Winkler, J., Koda, E., Červenová, J., Napieraj, K., Żółtowski, M., Jakimiuk, A., Podlasek, A. & Vaverková, M. D. (2024). Fragmentation and biodiversity change in urban vegetation: A case study of tram lines. *Land Degradation & Development*, *35* (5), 1734–1747. https://doi.org/10.1002/ldr.5017

Winkler, J., Koda, E., Skutnik, Z., Černý, M., Adamcová, D., Podlasek, A. & Vaverková, M. D. (2021). Trends in the succession of synanthropic vegetation on a reclaimed landfill in Poland. *Anthropocene*, *35*, 100299. https://doi.org/10.1016/j.ancene.2021.100299

Wittig, R. & Lienenbecker, H. (2003). Sandtrockenrasen auf Bahnhöfen in Ostwestfalen. *Naturwissenschaftlicher Verein für Bielefeld und Umgegend*, *43*, 259–284.

ZMIANY ROŚLINNOŚCI W ZALEŻNOŚCI OD PORY ROKU NA WYBRANYM ODCINKU LINII KOLEJOWEJ W REGIONIE MORAW POŁUDNIOWYCH (CZECHY) – STUDIUM PRZYPADKU

STRESZCZENIE

Linie kolejowe stanowią ważny element liniowej infrastruktury transportowej. Monitorowany odcinek jest częścią linii łączącej Wiedeń z Krakowem, której budowa rozpoczęła się w 1837 roku. Celem pracy była ocena składu gatunkowego roślinności na wybranym odcinku linii kolejowej. Ocenę przeprowadzono

metodą obrazowania fitocenologicznego w 2021 roku w miesiącach kwiecień, czerwiec, sierpień i październik. Podczas monitoringu odnotowano łącznie 31 gatunków roślin występujących w podtorzu danego odcinka. Wyniki wskazują, że monitorowany odcinek charakteryzuje się stosunkowo bogatą i różnorodną gatunkowo roślinnością, której skład i pokrycie zmieniają się w trakcie okresu wegetacyjnego. Roślinność wpływa nie tylko na stabilność strukturalną linii kolejowej, ale może również wpływać na płynność i bezpieczeństwo transportu kolejowego. Z tych powodów regularny monitoring i ocena roślinności powinny stanowić integralną część utrzymania eksploatacyjnego infrastruktury kolejowej.

Słowa kluczowe: roślina, bioróżnorodność, obszar antropogeniczny, roślinność antropogeniczna, kolej

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THE COMPLEX REMODELLING OF ACADEMIC BUILDINGS: THE CASE STUDY OF THE WATER CENTRE AT WARSAW UNIVERSITY OF LIFE SCIENCES (SGGW) CAMPUS

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ABSTRACT

This article examines the modernisation of higher education buildings. It includes a literature review of scientific works on the subject. The recently developed concept project for the modernisation of the Warsaw University of Life Sciences (SGGW) Water Centre building in Warsaw contained a wide range of works encompassing large-scale interventions involving remodelling, renovation, reconstruction and expansion of the existing building. The aim of the article is to examine the possibilities of adapting and optimising both the interior and exterior space through the use of contemporary, computer-aided design methods and incorporating sustainable development aspects. The research hypothesis is that a holistic approach to modernisation, integrating various industries and technologies, can significantly improve the functionality, energy efficiency, and accessibility of the building, and improve the development of the surrounding area. The research method adopted is a review of current literature on the topic and a case study of the Water Centre project on the SGGW campus in Warsaw. The results of the case study analysis indicate a number of problems related to the existing infrastructure and opportunities for improvement through the implementation of a design concept that takes into account the sustainable development goals (SDGs). The conclusions of the paper emphasise the need for interdisciplinary collaboration and a comprehensive approach that considers economic, social, and environmental aspects when modernising buildings with complex functions, which can contribute to improving the quality of space and meeting the needs of various user groups.

Keywords: campus modernisation, renovation, architecture, urban planning, BIM, sustainable development, SGGW

INTRODUCTION

Environmental problems caused by rapid urbanisation are causing countries to turn to sustainable development in the social and economic spheres. As carriers of educational and research activities, universities consume numerous resources and could shoulder more responsibility in ensuring sustainability. Many countries have developed and implemented sustainable policies for university campuses, which have increased diversity in campus

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construction. Universities, as major centres of education and research, consume large amounts of energy, water, and materials, and therefore bear a particular responsibility to lead by example in sustainability. In response, many countries have introduced dedicated sustainable-campus policies and initiatives, which have significantly increased the variety of approaches and designs in campus planning and construction (Chen, Cheng & Li, 2022).

The Warsaw University of Life Sciences (SGGW) plays a key role in promoting sustainable development in Poland. Implementing pro-environmental initiatives not only contributes to environmental protection and the rational use of its resources but also provides practical education for the academic community and society. The university belongs to numerous alliances and organisations bringing together universities.

The SGGW participates in international networks and alliances that directly address sustainable development, natural resource management, life sciences, and sustainable agriculture and forestry. In addition to the European universities alliance, UNI-GREEN focused on sustainable agriculture, green biotechnology, and environmental sciences, SGGW is a member of Euroleague for Life Sciences (ELLS), a network of leading European universities in the life sciences, focused on natural resource management, and agricultural, forestry, and environmental sciences. Its primary goals are education and research for the sustainable use of natural resources, bioeconomy, and solutions to climate change.

The SGGW is a member of the Association for European Life Science Universities (ICA), an association of over 50 European universities specialising in agriculture and life sciences. This organisation promotes education and research in the fields of life sciences, sustainable agriculture, food security, environmental protection, and bioeconomy. It organises numerous initiatives directly related to the UN sustainable development goals (SDGs), including the biodiversity challenge. The SGGW also actively participates in the CASEE Network – the regional arm of the ICA Board for Central and Eastern Europe, focused on the sustainable development of agriculture and natural sciences in Central and Eastern Europe.

Membership in the aforementioned organisations demonstrates the university's far-reaching ambitions in achieving sustainable development goals. According to the university's website, researchers from the SGGW's research institutes are engaged in projects that comprehensively contribute to the implementation of sustainable development principles across the entire campus and in the university's experimental facilities. One objective result of the SGGW's research in the area of sustainable development was its high ranking in the Impact Rankings, the only international ranking of universities based on the UN sustainable development goals (SDGs). The ranking aims to demonstrate the importance of higher education institutions in building a sustainable world and promote universities that work to address the greatest challenges of our time. The SGGW is gradually implementing systems that reduce energy consumption and utilise renewable energy sources. This began with the installation of energy-efficient lighting and photovoltaic panels and heat pumps. The first installations were completed in one of the student residences, in the sports facilities, and at the SGGW Forest Experimental Station in Rogów. In 2023, the photovoltaic panel system was expanded to a capacity of 650 kW on the university campus and 300 kW in the university experimental facilities. Electric vehicle charging points were also installed on the campus. Temperature monitoring and regulation systems linked to the control of heating substations, as well as ventilation and air conditioning monitoring systems, are used in the SGGW buildings. Thermal modernisation of the buildings is ongoing, and systems enabling significant automation of the operation of teaching and administrative facilities are being installed. Activities are also underway to optimise the use of cleaning products and paper for hygiene purposes (Biuro prasowe SGGW, 2025).

MATERIAL AND METHODS

The aim of this article is to analyse a case study of the modernisation of the building in question, taking into account original research methods and modern technologies. Conducting such studies and research can contribute to deepening specialised and detailed knowledge in the field of architecture and urban planning

and improving the solutions used in buildings with this and similar functions. The results indicate a number of problems related to the existing infrastructure and the considered design options. The aim is to analyse the case study, and the manuscript fills a research gap related to the lack of research on this aspect. This lack of research is related to the rarity and low number of similar projects and the limited scope of activities undertaken. Furthermore, a discussion is sought to be developed based on the issues presented in this work. This article fills the research gap related to the lack of detailed studies related to the comprehensive modernisation of facilities serving as higher education facilities that are parts of building complexes with a similar function located in an area with a specialised function, where various groups of users appear (the campus).

The concept project of modernisation of the Water Centre and its surroundings at the SGGW in Warsaw is a part of an internal competition (Golański et al., 2024). This project was created through the cooperation of a team of employees and doctoral students from the Department of Architecture in the Institute of Civil Engineering at the SGGW. The competition focused on developing design solutions for the modernisation of a building that is over a decade old and requires general renovation and changes due to various construction, functional, and spatial problems (Instytut Inżynierii Lądowej SGGW, 2025). This study was conducted based on detailed solutions from the project. It gathered considerations, original reflections, as well as comparisons of several variants of the completed project. These variants differed in the level of complexity, advancement of technical solutions, and complexity of the functional program, as well as economic aspects (Stefańska et al., 2023; Stefańska et al., 2025). The closing ceremony of the post-competition exhibition, held at the SGGW Library in November 2025, provided an opportunity for the project teams to meet and discuss the project with the university authorities at the Rector and Dean levels. Students from the 'Archi-Eco-Lab' Scientific Club involved in the project activities presented the project and related workshop activities at the XXIV International Scientific Conference – Defining the Architectural Space – Architecture and History in November 2025 (Juchimiuk, Golański, Donderewicz, Fabisiak & Sobczyński, 2025).

The research area encompasses selected fields of architecture, construction, environmental engineering, landscape architecture, and social sciences. While land development in the context of modernising buildings with complex functions, such as the SGGW Water Centre, may seem interesting and niche, it encompasses a multi-threaded architectural and urban planning concept.

The research tools and methods adopted in the case study described in the article were multi-objective and are described as follows. The author's scientific and professional archive served as a primary source of empirical data. A literature review and critical analysis were conducted, addressing the modernisation of public utility buildings with characteristics similar to those of the Water Centre, as well as the spatial development of university campuses. As part of the literature review in the area where the research was conducted, the ResearchGate, Web of Science, Google Scholar, Scopus, and *Acta Scientiarum Polonorum* database search engines were used as well as the Knowledge Base of the SGGW.

A case study was employed, focusing on the design concept for the modernisation of the SGGW Campus. The observational method was applied to conduct a visual assessment of the building and its surrounding area, as well as a technical evaluation of the existing condition prior to the development of the concept. The analytical method involved examining documentation, regulations, and input data, which facilitated formulating conclusions. Finally, a qualitative assessment was performed based on criteria identified through the literature review. The competition project for the modernisation of the SGGW Campus was selected as a case study example. The conclusions and discussion were supplemented with a literature review concerning research on similar implementations and projects with a comparable level of complexity.

RESULTS AND DISCUSSION

Renovation encompasses the comprehensive transformation of a property's function, layout, and appearance, frequently entailing significant structural modifications to adapt to evolving spatial demands. In contrast, refurbishment prioritises superficial enhancements, such as repairs and aesthetic refinements, to boost the usability and visual appeal while preserving the underlying structural integrity. Retrofitting, however, targets the incorporation of innovative technologies or features into extant structures to elevate energy performance, comply with contemporary regulations, or mitigate environmental impacts. Recent European research underscores the urgency of these distinctions in advancing sustainability, particularly in Central and Eastern Europe, where comprehensive retrofitting has demonstrated potential energy savings. These high-impact findings, with the former garnering citations for its policy implications amid EU decarbonisation efforts, emphasise how targeted retrofitting – beyond mere refurbishment – can align building upgrades with the European Green Deal's Renovation Wave, fostering economic viability and climate resilience in urban renewal projects (Fetting, 2020; Pacheco-Torgal, Granqvist, Vanoli, Bianco & Kurnitski, 2025).

Literature sources outline strategies for addressing the challenges in refurbishing buildings to achieve net-zero energy standards (Brophy & Lewis, 2012). A recurring emphasis is placed on adopting a multi--disciplinary approach that spans various fields, while ensuring consultants, contractors, and facilities managers align on a shared perspective. Energy considerations encompass diverse aspects across project phases, including design, management, and operation. The selection of materials and systems plays a key role in shaping the building's energy profile, encompassing both embodied and operational energy. Nevertheless, a low-carbon building must also meet human requirements; otherwise, the invested resources are rendered ineffective. Sustainability initiatives seek to enhance quality of life, particularly in terms of health and well--being, while minimising resource use.

The reviewed literature encompass resources that introduce an innovative method for renovating structures, merging elements from diverse expert fields, and incorporating principles of environmentally friendly architecture, architectural integrity, and optimal energy use (Leskovar & Premrov, 2019). This method highlights a number of frequently neglected attributes of structures that should be fully woven into the framework of renovation projects. These resources offer a summary of the primary strategies for renovation, categorised by their extent, depth, and key focuses. Moreover, they illustrate the ways in which particular advancements, such as expansions utilising modules made from wood, can support firms in the construction sector while strategising and advancing their upcoming manufacturing processes (Golański, 2016; Golański & Januszkiewicz, 2017; Golański, 2022). Multiple methodologies are employed when updating pre-existing edifices, and there exists a compelling requirement to merge the application of holistic and cross-disciplinary methods with current investigations, in addition to promoting education and increasing consciousness regarding their significance.

Summarising the literature research, it can be clearly concluded that the literature has shifted from purely technology-driven retrofits to socio-technical processes where technical excellence, rigorous management, digital integration, and genuine occupant partnership are equally important. Campuses that treat modernisation as an ongoing, participatory, data-informed process – rather than a checklist of green features – achieve the deepest and most durable sustainability gains.

Circular economies – the drive to minimise waste and maximise the use of resources, which has a positive impact on sustainable development – are gaining popularity.

In the coming years, further development and implementation of innovative solutions are expected, such as the widespread use of renewable energy to reduce greenhouse gas emissions and the pursuit of carbon neutrality in cities (Juchimiuk, 2015; Østergaard, Duic, Noorollahi, Mikulcic & Kalogirou, 2020).

From the reviewed literature, sustainable modernisation of university campuses consistently revolves around integration, user involvement, and long-term performance rather than isolated technical upgrades. The most critical recurring aspects can be grouped as follows:

- holistic and phased frameworks,
- active user and stakeholder engagement,
- closing the performance gap through monitoring and feedback loops,
- digital tools and information management,
- certification systems as project-management and communication tools,
- sustainability: energy- and material-efficient, circular economy,
- context-specific typological responses,
- balancing top-down standards with bottom-up demands.

Successful retrofits treat buildings as complex systems. The strongest frameworks (Ahmed, Mateo-Garcia, Arewa & Caratella, 2021; Ahmed, Dewidar, El-Hakeem & Guirguis, 2025) move systematically from diagnosis and benchmarking through technical intervention to monitoring and feedback. This phased approach prevents the common energy-performance gap (where predicted savings are not achieved in reality) and ensures that envelope upgrades, heating, ventilation and air conditioning (HVAC) renewal, lighting, and renewables are prioritised according to actual campus needs and payback periods.

Almost every paper emphasises that occupants (students, faculty, staff) must be involved early and continuously. Pre- and post-occupancy surveys plus participatory workshops dramatically increase acceptance of measures (e.g., new temperature set-points) and sustain energy savings (Ahmed et al., 2021). The Chinese context reveals that comfort and functionality often outweigh pure environmental criteria in users' minds; ignoring this leads to resistance or misuse of green features (Chen et al., 2022).

Low-energy renovation is not a one-time event. Continuous commissioning, real-time data dashboards, post-occupancy evaluation (Ahmed et al., 2021), and the digital platform (Carrasco-Beltrán et al., 2024) are essential to verify that modernised buildings actually perform as designed and to correct deviations quickly.

Modernisation projects generate enormous amounts of data, such as as-built drawings, energy models, maintenance logs, etc. (Zawada, Donderewicz, Gertner & Rybak-Niedziółka, 2024). Campus 2.0 demonstrates that a centralised BIM-based platform reduces errors, speeds up decision-making, and enables user-friendly interfaces (mobile apps, gamification) that further reinforce sustainable behaviour (Carrasco-Beltrán et al., 2024).

Piętocha (2024) positions BREEAM, LEED, and DGNB not merely as labels but as structured methodologies that force campuses to address the energy, materials, water, health, and management categories systematically (Piętocha, 2024). Achieving a high rating provides visible proof of commitment and often unlocks funding or regulatory advantages (Donderewicz & Zawada, 2024). Early integration of renewable energy sources (RES) technologies with an architectural envelope may benefit the effective energy efficiency of the buildings and areas (Juchimiuk, 2022a; Juchimiuk, 2022b).

Architectural and engineering solutions such as climate-friendly building technologies produced from renewable materials like engineered wood (CLT, LVL, glulam, KVH) contribute strongly to the overall environmental performance of the building in terms of embodied and operational energy (Berge, 2009; Maier, 2021; Stefańska, Cygan, Batte & Pietrzak, 2021; Dukarska & Mirski, 2023; Starzyk, Cortiços, Duarte & Łacek, 2025), life cycle assessment, and circular economy (deconstruction, re-use), addressing sustainable development and its goals (Golański & Januszkiewicz, 2017; Starzyk et al., 2025). Early integration of renewable energy systems into the building envelope is vital in developing innovative engineering solutions for energy-efficient architecture (Juchimiuk, 2022a).

While horizontal sprawl is common for traditional campuses. Some researchers argue that vertical or high--density development (especially in land-scarce megacities) can drastically cut per-capita energy and land use by shortening transport distances, enabling district energy systems, and integrating greenery at multiple levels (Piętocha, Li & Koda, 2025). This paradigm is particularly relevant when campuses must expand their enrolment without acquiring more land.

Official green-campus indicators (common in China, Europe, and North America) and global certifications provide rigour, but Chen et al. (2022) warn that strict compliance alone can produce buildings that users dislike or circumvent. The most effective modernisations hybridise regulatory requirements with localised user priorities.

Case study

The design philosophy behind the renovation project of the Water Centre and its surroundings at the SGGW Campus in Warsaw envisions a substantial enlargement and addition of upper levels to the current structure, aimed at completing the edge of the SGGW Campus and establishing a fresh, prestigious area. A central feature involves transforming the nature of the main indoor space by incorporating multiple links to outdoor vistas and fostering interactions between the internal and external environments. These communication zones, laid out along defined axes, are intended to encourage visitors to discover the building and provide visual access to the broader campus grounds, thereby setting up optimal circumstances for showcasing gatherings and programs held at the SGGW Water Centre – especially those focused on advocating cutting-edge and eco-friendly approaches in building practices, architectural design, and landscaping.

The building has been in operation since 2010. The 1.5-hectare facility includes a water park with a model river and a research and teaching building (Fig. 1). The SGGW Water Centre is the largest research facility in Poland dedicated to water, housing 20 laboratories in various fields. Its original function as a highly specialised research and teaching facility, at that time not integrated with the SGGW Campus, had largely been exhausted, a fact clearly revealed in user group research and participatory workshops. Problems with functional inconsistencies were compounded by the deteriorating technical condition and the need to adapt the building's envelope to current thermal insulation requirements. The extensive renovation work, which included thermal modernisation, the repair and replacement of HVAC systems, the reconstruction of the internal envelope, introducing fundamental changes to the building's use, and the demolition work provided the opportunity for an optimised and highly efficient expansion of the building, making it both self-sufficient in terms of energy generation and integrated with the urban environment, bordering zones with different primary functions (the SGGW Campus and residential developments).

This project was created in cooperation with a team of staff and doctoral students from the Department of Architecture in the Institute of Civil Engineering at SGGW. The competition involved preparing and presenting design solutions for the modernisation of a building that is over a decade old and requires changes due to a series of construction, functional, and spatial problems. This study was carried out based on the detailed solutions of the project. It gathered considerations, original reflections, as well as comparisons of several variants of the completed project. These variants were distinguished by the level of complexity, advancement of technical solutions, complexity of the functional program, and economic issues. The conclusions and discussion were supplemented with a literature review concerning research on similar implementations and projects with a comparable level of complexity.

Social interaction constituted a significant contribution by providing ongoing review of the developing design concept and delivering direct review (feedback loop). User involvement in the building's design process was achieved through interviews and workshops organised by the lecturers, as well as external partners (Other Space Foundation and the Academy of Young Architects) involving high school youth, seniors, dog owners, SGGW students, academic and teaching staff, and local residents, as well as through

direct engagement in the design process by assisting and creating original studies that humanise the space around the SGGW Water Centre, with these studies forming an integral part of the design concept (architecture students) (Vietrova, Vasyliev & Swacha, 2025). A fundamental component of the development was the design credo, which defined the pattern language concerning the spatial arrangement, cultural and social aspects, neurodiversity needs, and a broadly understood strategy for implementing blue-green systems. The multi--thematic project is undoubtedly characterised as the Green Flagship of the SGGW, encompassing aspects of biodiversity. Local identity (*genius loci*) is expressed through the presence of pavilion structures (follies) and a footbridge with clearly articulated spatial features (Fig. 2). The building itself was conceived as a demonstrator object for pro-environmental architectural solutions, methods of shaping green buildings, and sustainable construction technologies.



Fig. 1. Existing SGGW Water Centre

Source: own work.

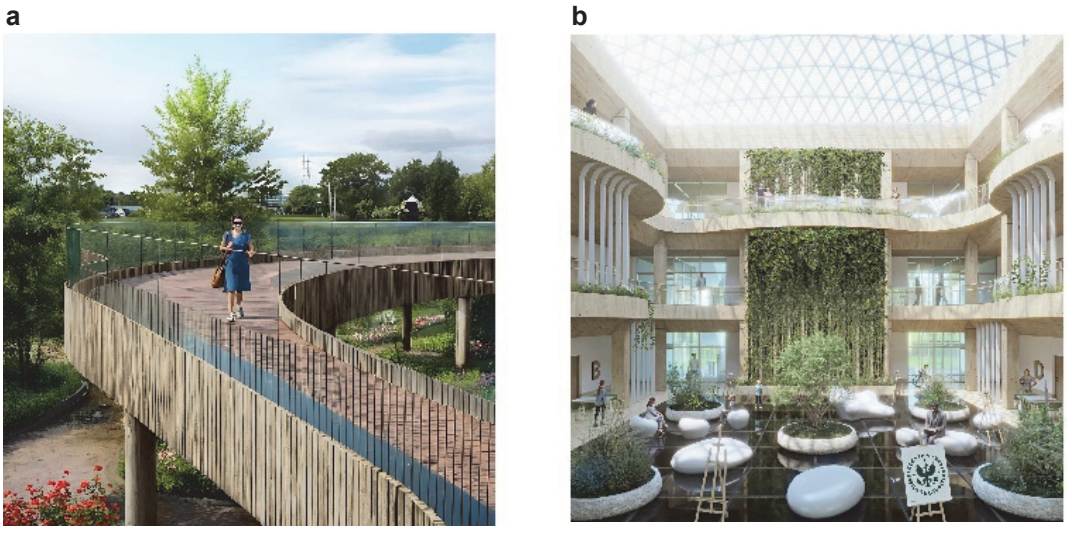


Fig. 2. Concept project of SGGW Water Centre with neighbouring area: a – external elevated pathway, b – atrium with greenwall and gridshell skydome

Source: own work.

The team's work resulted in a fully fledged concept for the modernisation of the building and its surroundings. The solutions consisted in the implementation of pro-environmental measures that would fit into the prevailing trends and practices from international implementations. The guiding idea was to create a consolidated open space tailored to the needs of various user groups, ranging from students, lecturers and administrative staff, to the local community and guests from abroad. The proposal integrated, to the greatest extent possible, the 17 SDGs, which, together with the 169 associated tasks, form the global Agenda 2030. These encompass three dimensions of sustainable development: economic, social, and environmental. All three fundamental aspects of sustainable development (social, environmental and economic) were taken into account and expressed in the concept (Fig. 3).



Fig. 3. Concept project of SGGW Water Centre with neighbouring area. Environmental aspects addressed in the concept project: a – view along Ciszewskiego street, b – Plans of levels –1 and 0

Source: own work.

Sustainable design solutions

The reconstruction of the SGGW Water Centre aims to transform the facility and its immediate surroundings and to give it a new identity as a 'green' showcase for the SGGW that promotes directions related to renewable energy sources and materialises the SGGW's pro-ecological ambitions. The concept assumes the expansion of the building in a way that emphasises its function as a corner closure of the SGGW Campus, a change in the character of the building's central interior, and the introduction of a series of external visual connections and interior-exterior linkages. It is essential to create central representative spaces with an axial character through the implementation of a communication system that provokes exploration, visually opens up the SGGW Campus area, and enables broad promotion of events and activities carried out in the New Centre for Innovation.

The main idea of the modernisation is based on creating high-quality spaces with respect for nature. The solutions introduce green elements into the interiors, building façades, and roof surfaces and implement diverse forms of green space development – from arranged greenery to areas of spontaneous vegetation aimed at realising the idea of biodiversity. Ecological, spatial, and social aspects play a significant role. They constitute an exposition of processes and technologies related to blue-green infrastructure.

The design inspiration is derived from traditional Chinese gardens. They represent a combination of nature, philosophy, and art, reflecting a harmony between humans and nature. Characteristic elements of such gardens form a kind of landscapes containing ponds and streams (symbolising the sky), stones (representing mountains and earth), pavilions and gazebos (places for rest and contemplation), bridges (symbolising the transition between different states of being), and vegetation (carefully selected to bloom in different seasons, providing a changing, beautiful landscape).

The renovation initiative for the SGGW Water Centre aims to improve the structure's overall utility by introducing extra areas dedicated to learning, research endeavours, meetings, displays, and various gatherings, all while aligning with objectives for sustainable progress (Fig. 2).

Significant alterations to the functionality encompass:

– Converting spaces in the basement (Level −1) into areas for instructional purposes, including a virtual reality laboratory.
– Adjusting the layout on the main floor (Level 0) to incorporate a retractable, temporary seating arrangement capable of holding 100 individuals.

The extension to the facility entails (Table 1):

– Expanding the available floor space by substituting the current surface-level parking lot with a subterranean parking facility.
– Extending the footprint on the ground level (Level 0) and the upper level (Level +1) in proximity to the entrance of the SGGW Campus.
– Constructing additional sections on Levels 0, +1, and +2 to accommodate classrooms for education and observation decks offering sightlines across the SGGW Water Park.

Table 1. Area schedule

Area	Gross floor area (GFA)
Existing	4,768 m²
New area	3,862 m²
Total area after renovation	8,630 m²

Source: own work.

Furthermore, the architectural plan incorporates plant life within the internal spaces, exterior walls and rooftop areas, and fosters ecological diversity by combining formally designed green zones with regions of naturally occurring flora (Fig. 4).

The core concept behind the design is to establish a superior environment that honours the natural world and serves as a demonstration of sustainable biophilic principles in building design (Table 2). This goal is realised through the inclusion of verdant features inside the building, along its outer surfaces, and across the roof expanses, thereby reinforcing a commitment to visual appeal that blends seamlessly with the environment. The landscaping surrounding the SGGW Water Centre features both meticulously planned plantings and zones of unmanaged growth, intended to enhance biological variety. The initiative places strong emphasis on environmental, layout-related, and community-oriented elements, which are intended to showcase various mechanisms and innovations associated with blue-green systems. As a result, visitors can directly witness the operations of systems like water reclamation or plant care protocols, thereby amplifying the site's role in education.

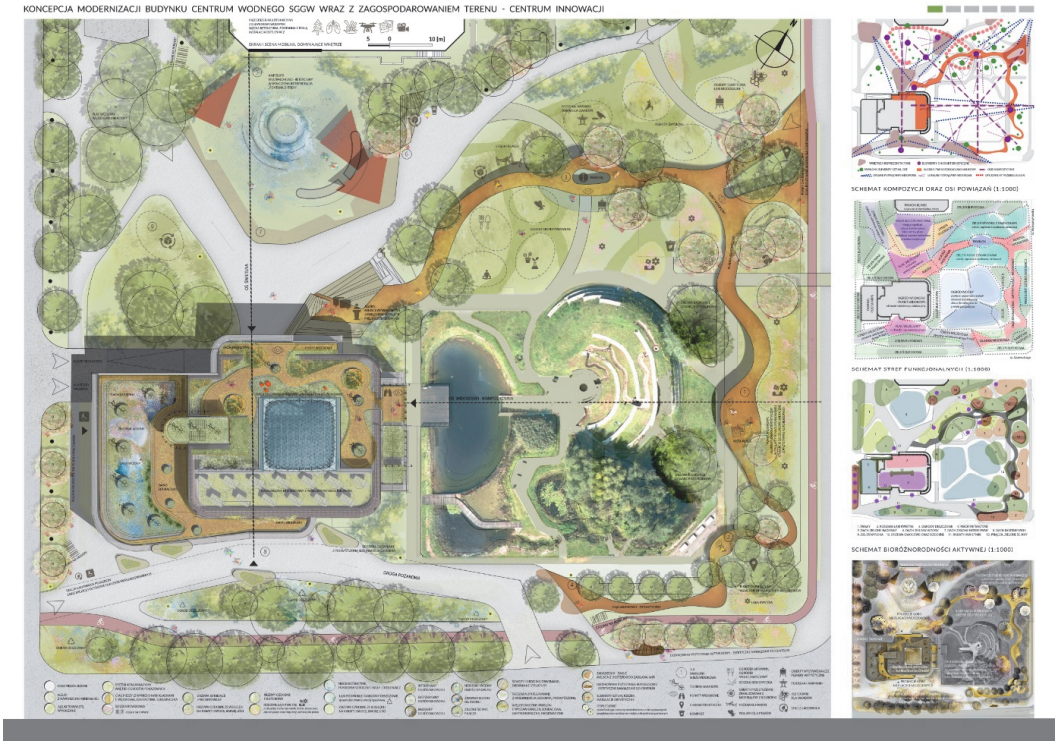


Fig. 4. Concept project of SGGW Water Centre with neighbouring area. Site plan

Source: own work.

Table 2. Stages of remodelling process of SGGW Water Centre and campus surroundings in Warsaw

Sustainable building solutions	Design and engineering field
Prefabricated structure made of glued- and cross-laminated timber	Building materials Construction technologies Structural design
Photovoltaic panels: photovoltaic (PV)/building integrated photovoltaics (BIPVT)/ /organic photovoltaic (OPV)/perovskites – tracking systems, agrivoltaics	Architectural design Building envelope Renewable energy sources (RES) design Landscape design
Green wall	Interior design Landscape design
Artificial mist fountain	Interior design Heating, ventilation and air conditioning (HVAC)

Source: own work.

The language of patterns (credo) contained in the concept of land development is an emanation of process-oriented thinking, rather than the localisation of individual functions. Its foundation was a multi-layered and multi-faceted field interview. This made it possible to identify visual features and hidden characteristics of the subject area and to discover values strongly associated with the terrain as a place,

the definition of this place, and its redefinition anew. As we know, 'place' in urbanism does not exist without people. This is precisely what distinguishes a place from a 'non-place'. To build a 'place' with its unique *genius loci*, it is essential to combine tradition, culture, form, and an appropriate quality of life. In the subject project, tradition is expressed through myths, culture through the heritage of academic life, form through art, and quality of life is created by pro-ecological solutions (land art and reuse) (Borkowski & Winiarska, 2025). Culture as the heritage of academic life is expressed via the Axis of New Horizons – metaphorically and literally intersecting the volumetric object of the Water Centre – this is a compositional axis connecting points that are the horizon lighthouse, the light lighthouse, and the perspective lighthouse. In turn, form is expressed through art. It accompanies the mythological, meandering form of the Path of Knowledge and Innovation. There, in the form of 'milestones', a platform of 'wandering artifacts' will be launched, illustrating the fragility of human fates and similarly the fragility of the life of works of art, sometimes extracted from the oblivion of history, but just as often falling into forgetfulness. The awareness of the accompanying overall new quality of life is demonstrated through the location around the Water Park of a group of pavilions erected on reuse principles. These are the Circular Towers Pavilions, the Sustainable Development Pavilion, the Event – Organic Pavilion, and the Resilience Tower. This location constitutes an allegorical dimension of humanity's struggles to save the Globe and its natural environment (here – towers, historically, as a defensive form).

The design concept of the New Innovation Centre intentionally references the 'Water' past as well as the green, innovative future. The concept respects the needs of the academic community and the university's conference ambitions. It assumes the use of elements from the former fountain in the building and structural roof elements as decor, building material for small architecture, pavilion construction, or viewing bridges. These elements aim to visually connect with the previous form and function of the SGGW Water Centre. Such actions give the place a unique identity and emphasise the role of a sustainable approach to modernisation investments and the promotion of circular construction. Elevated green flower beds and solid benches with versatile orientation create transparent recreational interiors, while simultaneously contributing to the unsealing and greening of the surroundings of the New Innovation Centre. The use of solid, durable materials such as steel, natural stone and glued-laminated timber ensures a sustainable and resilient structure.

The structure of the newly designed part of the building consists of columns, beams, and cross-braces made of glued-laminated timber, as well as floors executed in CLT technology. CLT floors combine the properties of natural wood with prefabrication technology, allowing for large spans of structural elements and quick assembly on the construction site. Connections between wooden elements are made using wooden joint systems and steel connectors.

The applied tracking photovoltaic panel systems contribute to reducing electricity consumption and lowering the costs associated with maintaining the facility. They also serve as an element of the educational path designed on the roof. It is accessible to users and visitors of the facility. The photovoltaic system is hidden behind the attic.

In the atrium, a green wall is proposed, which will serve as the main decorative element of the interior and provide a backdrop for presentations – thus, this solution will be promoted in the media. The green wall should be located in a room with a stable temperature ranging from 18°C to 21°C.

Inspired by Chinese gardens, an artificial mist fountain is proposed. It is generated from normal water by forcing it through aerosol nozzles under high pressure. It can increase air humidity, lower the temperature, and create a mystical aura. The use of the 'fountain' as a carrier for projections – holograms – is planned. This solution represents a reference and continuation of the object's previous function in water research.

Building information modelling (BIM) plays a pivotal role in architectural design by enabling precise simulations of energy performance and resource utilisation, allowing designers to minimise environmental impacts such as carbon emissions and waste generation from the outset. It supports the integration

of sustainable features like green roofs, solar panels, and efficient water systems, ensuring that buildings align with certifications such as LEED or BREEAM to achieve long-term ecological benefits (Piętocha, 2024). BIM also facilitates collaborative lifecycle assessments among stakeholders, optimising material choices and operational efficiencies to promote biodiversity, reduce urban heat islands, and enhance overall resilience to climate change (Juchimiuk & Golański, 2025). An example of this application is the BIM model used for the concept design of the SGGW Water Centre building in Warsaw, as referenced on Figure 5.

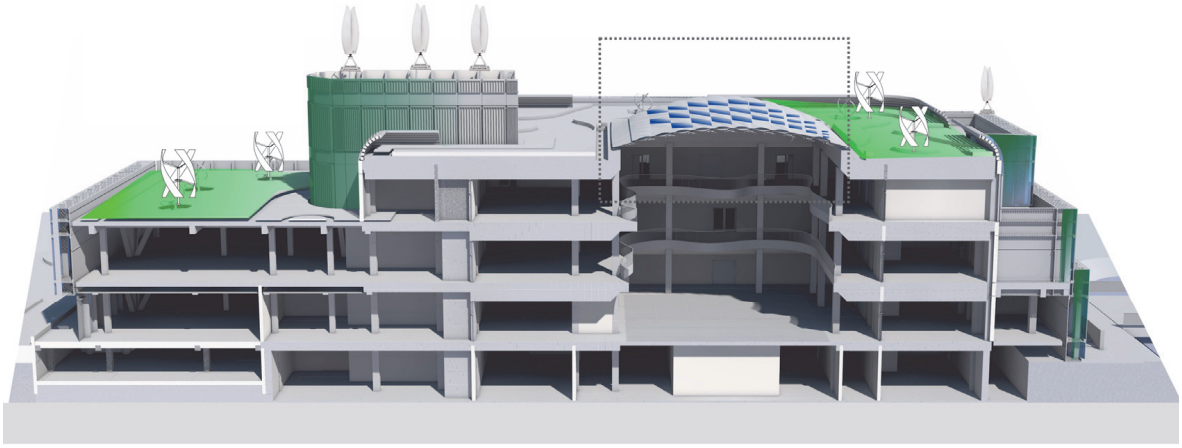


Fig. 5. BIM model of water centre used in concept design process for project of environmental aspects addressed in concept project of SGGW Water Centre

Source: own work.

Project phases

The modernisation project for the SGGW Water Centre in Warsaw was strategically developed in phased variants to allow for efficient resource allocation, reduced operational disruptions, and progressive integration of sustainable features (Table 3). In Stage I, the focus is on constructing an underground parking hall and expanding Level 0, which lays the foundational infrastructure for improved accessibility and functionality. This initial phase ensures that core structural enhancements are completed before advancing to the upper levels, minimising the risks associated with simultaneous large-scale works. Stage II involves the expansion of Level +1, building on the groundwork to incorporate additional spaces for academic and innovative activities while maintaining the site's historical water-themed elements. By sequencing the project this way, the design team can address immediate needs like parking without compromising the overall vision of a green, innovative centre. Stage III encompasses the expansion of Level +2, along with the installation of a new skylight and green roofs, which enhance the natural lighting, energy efficiency, and environmental integration. These elements promote sustainability by incorporating photovoltaic systems and green walls, aligning with circular economy principles (Fig. 6). Finally, Stage IV, which is completely independent, handles the land development, providing flexible timing to optimise the landscaping, recreational areas, and external connections. This phased approach not only respects budget constraints and timelines but also enables ongoing monitoring and adjustments based on feedback from stakeholders. Overall, the variant-based development underscores a holistic strategy that balances innovation, heritage preservation, and ecological responsibility for the New Innovation Centre.

Table 3. Stages of remodelling process of Water Centre and surroundings at SGGW Campus in Warsaw

Stage	Description
I	Construction of the underground parking hall and expansion of Level 0
II	Expansion of Level +1
III	Expansion of Level +2, including a new skylight and green roofs
IV	(Completely independent) Realisation of land development

Source: own work.

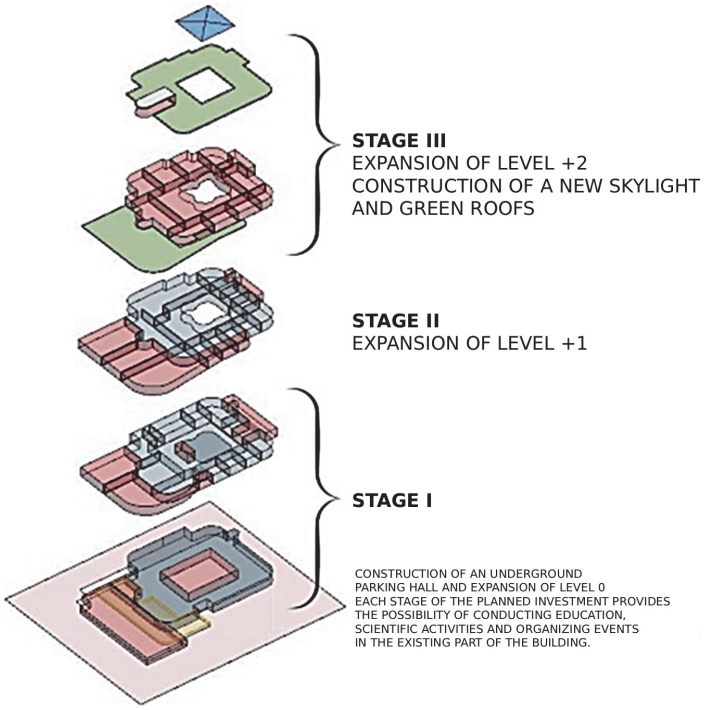


Fig. 6. Concept project of SGGW Water Centre with neighbouring area. Site plan

Source: own work.

CASE-STUDY RESULTS

The research findings identified sustainable design aspects related to the modernisation of the subject building. Criteria and keywords were adopted that correspond to architectural and urban issues in relation to the modernisation, including the general renovation and retrofitting of buildings with complex functions, similar to the subject building of the SGGW Water Centre.

The table lists eight key criteria from theoretical research on sustainable renovation, assessed for the SGGW Water Centre project in Warsaw, with '+' indicating fulfilment in areas such as holistic frameworks, user engagement, digital tools, sustainability (energy/material efficiency and circular economy), context-specific responses, and balancing standards with demands, while '–' marks shortcomings in performance monitoring/feedback and certification systems (Table 4).

Table 4. Architectural and engineering design solutions

Recurring aspects in sustainable renovation	Criteria met in project
Holistic and phased frameworks	+
Active user and stakeholder engagement	+
Closing the performance gap through monitoring and feedback loops	–
Digital tools and information management	+
Certification systems as project-management and communication tools	–
Sustainability: energy- and material-efficient, circular economy	+
Context-specific typological responses	+
Balancing top-down standards with bottom-up demands	+

Source: own work.

The project's holistic and phased frameworks effectively integrate remodelling, renovation, reconstruction, and expansion, aligning with theoretical models for comprehensive sustainable upgrades in higher education buildings. Active user and stakeholder engagement is demonstrated through designs that cater to academic needs and conference goals, promoting inclusive participation as advocated in research. However, the lack of closing the performance gap via monitoring and feedback loops overlooks a critical theoretical aspect for ensuring ongoing efficiency and adaptability. Utilisation of digital tools and information management, such as CLT prefabrication and photovoltaic systems, supports streamlined processes and innovation, meeting scholarly recommendations for tech-driven renovations (Fig. 7). The absence of certification systems as project-management and communication tools misses an opportunity to leverage standards for validation and outreach, contrary to the theoretical emphasis. The strong focus on sustainability through energy and material efficiency, including circular economy practices like material reuse, embodies core research principles for eco-friendly modernisation. Context-specific typological responses are achieved by tying the design to the site's water heritage and green future, creating a tailored approach as suggested in the literature. Balancing top-down standards with bottom-up demands is evident in features like green spaces and durable materials that address both regulations and user preferences.

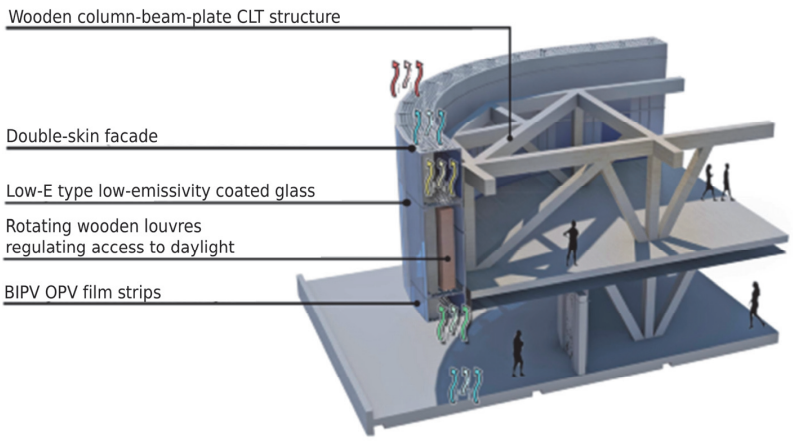


Fig. 7. Integration of building-integrated organic photovoltaic (BIPV) double-skin façade featuring organic photovoltaic coating (OP) with engineered wood structure

Source: own work.

Overall, the project's alignment with six out of eight criteria highlights its potential as a model for sustainable academic building transformations. Incorporating monitoring mechanisms and certifications in future phases could address the gaps, enhancing the alignment with full theoretical frameworks for long-term impact.

The modernisation effort for the SGGW Water Centre exemplifies a thorough application of sustainable development principles, encompassing not only construction and material choices but also operational frameworks (Table 5).

Table 5. Architectural and engineering design solutions

Sustainability aspect	Architectural and engineering design solutions
Social	Use of social participation tools
	Humanisation of the SGGW Campus space by creating quiet zones for neurodiverse individuals and areas with a distinct local identity (*genius loci*)
	Improvement of the city's aesthetics, organisation of SGGW Campus space
	Creation of a landmark for the SGGW Campus – a flagship building with a clearly pro-ecological character that strengthens the image of SGGW as a green higher education institution
	Demonstration of pro-environmental construction technologies
Environmental	Use of ecological materials
	Thermal modernisation
	Use of renewable energy sources and their integration with the building's external partitions
	Re-use strategy
	Design for deconstruction
	Biodiversity
	Greening
Economic	Dematerialisation
	Circular economy
	Energy efficiency
	Design for manufacturing and assembly (DfMA)
	Improvement of building's technical condition
	Maintenance costs reduction
	Increasing the surface area of buildings, return on investment

Source: own work.

DISCUSSION

The SGGW Campus modernisation transcends a conventional retrofit by embedding Agenda 2030 into the physical, social, and economic fabric of this piece of academic infrastructure. Its triple-loop learning framework – technical innovation, participatory governance, and circular materiality – offers a scientifically robust, scalable archetype for sustainable urban regeneration and green construction transformation (Juchimiuk & Golański, 2025).

Renovating mixed-use, mid-sized public sector buildings provides an ideal platform to advance sustainability by incorporating energy-efficient systems that reduce operational expenses and mitigate environmental impacts. Passive solar strategies, including optimised window placements and external shading, effectively diminish the dependence on artificial climate control in these versatile environments. Pro-ecological engineering solutions, such as rainwater harvesting and greywater systems, enhance water efficiency and reflect the public sector's commitment to sustainable resource management. Selecting recycled materials like reclaimed wood and sustainable insulation minimises embodied carbon emissions while extending the building's service life (Golański, Juchimiuk, Kwiatkowski & Figat, 2025). Addressing neurodiversity in renovations involves integrating sensory-friendly elements, such as tuneable lighting, sound-absorbing materials, and dedicated calm spaces to accommodate users with conditions like autism or ADHD. Adaptive reuse preserves historical features while enhancing building envelopes to achieve nearly zero-energy performance. There is a pressing need for intensive actions to green the interiors of buildings in urban spaces, as this fosters biodiversity by introducing plant life that supports local ecosystems and improves air quality. Such greening initiatives also promote users' mental health by creating restorative environments that reduce stress and enhance well-being through biophilic connections to nature. Green roofs, vertical gardens, and indoor plant integrations not only bolster biodiversity but also contribute to thermal insulation and natural cooling in densely populated areas. Smart engineering with IoT sensors optimises energy use across mixed functions, ensuring seamless operation in retail, administrative, and communal areas. Social participation is encouraged via inclusive designs like accessible entrances, shared plazas, and stakeholder-involved planning to build community ownership. Modular approaches in renovations minimise waste and facilitate adaptable spaces for evolving needs without significant environmental harm. Life-cycle analyses guide decisions to harmonise ecological gains with economic sustainability in public projects. Neurodiversity-friendly features, including adaptable seating and intuitive signage, further ensure equitable access and comfort for all. Community engagement through workshops strengthens social ties, positioning the building as a vibrant civic centre. Integrating renewable energy sources, such as solar arrays and wind turbines, complements interior greening efforts by powering sustainable systems and reducing the reliance on fossil fuels. Finally, multi-sensory accessibility tools like tactile maps support neurodiverse individuals, while holistic greening strategies underscore the interplay between urban biodiversity, mental health benefits, and renewable energy adoption.

CONCLUSIONS

The modernisation of buildings with complex functions, such as the SGGW Water Centre, is complex and multifaceted. A holistic, multifaceted approach is necessary, integrating various disciplines and co-creating a project team divided by thematic areas (architecture, landscape design, structural design, construction technology, HVAC). The article examines the modernisation of higher education buildings, including research of scientific works on the subject. The recently developed concept project modernisation of the SGGW Water Centre building in Warsaw contained a wide range of large-scale interventions involving remodelling, renovation, reconstruction and expansion of the existing building. Modernising these types of buildings is important, brings benefits, increases the efficiency of existing buildings, and produces operational savings through energy efficiency. It results in the creation of better spaces that meet a range of regulations and the needs of various social groups, including those with disabilities. It also makes it possible to intensify and optimise the use of the functional spaces, creating more educational and conference rooms that meet applicable standards. This type of concept creates opportunities for implementing modern technology, including interactivity, VR, and AR technologies. Design variability is beneficial and justified for many reasons, allowing for personalised design solutions and more precise fulfilment of needs. However, it is important to be mindful of the drawbacks, obstacles, inhibiting factors, limitations, and challenges. In the future,

the modernisation process can be improved by paying attention to aspects such as social participation, sustainable development, and technology integration. Within this topic, research directions related to analysing the impact of modernisation on the environment, user health and well-being, and economic efficiency can also be identified. The impact of modernisation on the image of SGGW and its relations with its surroundings is also a significant aspect. One of the requirements of the investor was to turn the SGGW Campus into a landmark; a showcase building with a clearly pro-ecological character that strengthens the image of SGGW as a green higher education institution.

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All authors have read and agreed to the published version of the manuscript.

REFERENCES

Ahmed, E. K. A., Dewidar, K. M., Abd El-Hakeem, Y. & Guirguis, M. N. (2025). An integrated framework for sustainable retrofitting of existing university buildings. *Discover Sustainability*, *6* (38). https://doi.org/10.1007/s43621-024-00703-7

Ahmed, A., Mateo-Garcia, M., Arewa, A. & Caratella, K. (2021). Integrated performance optimization of higher education buildings using low-energy renovation process and user engagement. *Energies*, *14* (5), 1475. https://doi.org/10.3390/en14051475

Berge, B. (2009). Structural materials. In *The Ecology of Building Materials* (pp. 199–246). Routledge.

Biuro prasowe SGGW. (2025, October 18). *SGGW wdraża zasady zrównoważonego rozwoju na uczelnianym kampusie*. Retrieved from: https://media.sggw.pl/aktualnosci/802117/sggw-wdraza-zasady-zrownowazonego-rozwoju-na-uczelnianym-kampusie [accessed: 14.11.2025].

Borkowski, A. S. & Winiarska, W. (2025). The HBIM Model as a Source in the Building Reconstruction Process: A Case Study of the "Koprówka" in Celestynów, Poland. *Buildings*, *15* (9), 1442. https://doi.org/10.3390/buildings15091442

Brophy, V. & Lewis, J. O. (2012). *A green Vitruvius: Principles and practice of sustainable architectural design*. Routledge.

Carrasco-Beltrán, D., Serrano-Sierra, A., Cuervo, R., Valbuena-Bermúdez, C., Pavlich-Mariscal, J. A. & Granados-León, C. (2024). Digital Transformation in University Architecture: Optimizing Construction Processes and User Experience through CAMPUS 2.0 at Pontificia Universidad Javeriana. *Buildings*, *14* (10), 3095. https://doi.org/10.3390/buildings14103095

Chen, G., Cheng, L. & Li, F. (2022). Integrating Sustainability and Users' Demands in the Retrofit of a University Campus in China. *Sustainability*, *14* (16), 10414. https://doi.org/10.3390/su141610414

Donderewicz, M. & Zawada, K. (2024). Prospects for architecture and urban planning: Integration of BIM and 4.0 technology in the context of climate change. In T. Kozłowski (Ed.), *Defining the Architectural Space / Definiowanie Przestrzeni Architektonicznej* (Vol. 3, pp. 27–37). Wrocław: Oficyna Wydawnicza Atut, Wrocławskie Wydawnictwo Oświatowe. Retrieved from: https://dpa.arch.pk.edu.pl/wp-content/uploads/Defining-Architectural-Space-2024-3-03-DONDEREWICZ.pdf [accessed: 14.11.2025].

Dukarska, D. & Mirski, R. (2023). Wood-based materials in building. *Materials*, *16* (8), 2987. https://doi.org/10.3390/ma16082987

Fetting, C. (2020). *The European Green Deal (ESDN Conference Report, December 2020)*. Vienna: ESDN Office. Retrieved from: https://www.esdn.eu/fileadmin/ESDN_Reports/ESDN_Report_2_2020.pdf [accessed: 14.11.2025].

Golański, M. (2016). Thermal renovation of buildings with the use of straw – European experience. *Civil and Environmental Engineering Reports*, *23* (4), 61–68. https://doi.org/10.1515/ceer-2016-0051

Golański, M. (2022). Advances in digital design and fabrication of wooden architecture. *Architecturae et Artibus*, *14* (4), 37–54. https://doi.org/10.24427/aea-2022-vol14-no4-04

Golański, M., Donderewicz, M., Juchimiuk, J., Kwiatkowski, J., Łacek, P., Pożarowszczyk-Bieniak, M., Piętocha, A., Fabisiak, N., Kos-Podlaska, M., Kowalczyk, K. & Wysocki, M. (2024). *Koncepcja konkursowa modernizacji Centrum Wodnego na terenie Kampusu SGGW w Warszawie wraz zagospodarowaniem terenu – Centrum Innowacji*. SGGW, Warszawa [unpublished].

Golański, M. & Januszkiewicz, K. (2017). Free-form wooden architectural envelopes in terms of energy efficiency. In *17th International Multidisciplinary Scientific GeoConference: SGEM 2017* (pp. 555–562). Sofia: STEF92 Technology. https://doi.org/10.5593/sgem2017H/63/S26.070

Golański, M., Juchimiuk, J., Kwiatkowski, J. & Figat, A. (2025). The use of prefabricated wooden structures in sustainable construction, illustrated by the example of a public library. *Inżynieria i Budownictwo*, *81* (5), 569–573. https://doi.org/10.5604/01.3001.0055.2497

Instytut Inżynierii Lądowej SGGW. (2025, January). *Wyniki konkursu „Koncepcja modernizacji budynku Centrum Wodnego wraz z otoczeniem"*. Instytut Inżynierii Lądowej WBIS SGGW. Retrieved from: https://iil.sggw.edu.pl/wyniki-konkursu-koncepcja-modernizacji-budynku-centrum-wodnego-wraz-z-otoczeniem-2/ [accessed: 14.11.2025].

Juchimiuk, J. (2015). Energetyczna rewitalizacja miast w aspekcie wykorzystania odnawialnych źródeł energii. *Przestrzeń i Forma*, *23* (2), 73–86.

Juchimiuk, J. (2022a). Energy metamorphosis of cities and buildings. *Architecturae et Artibus*, *14* (4), 55–74. https://doi.org/10.24427/aea-2022-vol14-no4-05

Juchimiuk, J. (2022b). Renewable Energy Sources in Architecture of the World Expo. *Architecturae et Artibus*, *14* (4), 75–91. https://doi.org/10.24427/aea-2022-vol14-no4-06

Juchimiuk, J. & Golański, M. (2025). Factors and drivers of architectural form modelling in aspect of climate change. *Inżynieria Bezpieczeństwa Obiektów Antropogenicznych*, *3*, 30–41. https://doi.org/10.37105/iboa.277

Juchimiuk, J., Golański, M., Donderewicz, M., Fabisiak, N. & Sobczyński, Ł. (2025). ARCHI-ECO-LAB. Workshop method in the education of architecture students at the SGGW. Poster Session. In *XXIV International Scientific Conference – Defining the Architectural Space – Architecture and History* (pp. 32–33). Kraków: Politechnika Krakowska. Retrieved from: https://e-isbn.pl/IsbnWeb/onix/summary.html?record_id=4847872 [accessed: 14.11.2025].

Leskovar, V. Ž. & Premrov, M. (2019). *Integrative Approach to Comprehensive Building Renovations*. Springer International Publishing.

Maier, D. (2021). Building materials made of wood waste a solution to achieve the sustainable development goals. *Materials*, *14* (24), 7638. https://doi.org/10.3390/ma14247638

Østergaard, P. A., Duic, N., Noorollahi, Y., Mikulcic, H. & Kalogirou, S. (2020). Sustainable development using renewable energy technology. *Renewable Energy*, *146*, 2430–2437. https://doi.org/10.1016/j.renene.2019.08.094

Pacheco-Torgal, F., Granqvist, C-G., Vanoli, G. P., Bianco, N. & Kurnitski, J. (2025). *Cost-effective energy-efficient methods for refurbishment and retrofitting of buildings: Materials, technologies, optimization, and case studies*. Elsevier.

Piętocha, A. (2024). The BREEAM, the LEED and the DGNB certifications as an aspect of sustainable development. *Acta Scientiarum Polonorum. Architectura*, *23*, 121–133. https://doi.org/10.22630/ASPA.2024.23.9

Piętocha, A., Li, W. & Koda, E. (2025). The Vertical City Paradigm as Sustainable Response to Urban Densification and Energy Challenges: Case Studies from Asian Megacities. *Energies*, *18* (19), 5278. https://doi.org/10.3390/en18195278

Starzyk, A., Cortiços, N. D., Duarte, C. C. & Łacek, P. (2025). Timber Architecture for Sustainable Futures: A Critical Review of Design and Research Challenges in the Era of Environmental and Social Transition. *Buildings*, *15* (15), 2774. https://doi.org/10.3390/buildings15152774

Stefańska, A., Chudzińska, A., Kurcjusz, M., Sutkowska, M., Krawczyk, J. & Dixit, S. (2023). Urban energy recycling: An architectural road map. In M. J. Skibniewski & H. Miklos (Eds.), *Proceedings of the Creative Construction Conference* (*2023*) (pp. 645–649). Budapest: Budapest University of Technology and Economics. https://doi.org/10.3311/CCC2023-083

Stefańska, A., Cygan, M., Batte, K. & Pietrzak, J. (2021). Applications of timber and wood-based materials in architectural design using multi-objective optimisation tools. *Construction Economics and Building*, *21* (3), 105–121. https://doi.org/10.5130/AJCEB.v21i3.7642

Stefańska, A., Walasek, K., Kurcjusz, M., Warzecha, B., Koszewska, J. & Niemczak, P. (2025). Contemporary design of sustainable campus spaces: a case study of the extension of the Water Centre at the Warsaw University of Life Sciences – SGGW. *Acta Scientiarum Polonorum. Architectura*, *24*, 261–276. https://doi.org/10.22630/ASPA.2024.24.18

Vietrova, P., Vasyliev, P. & Swacha, P. (2025). Participatory planning of student campuses. Case studies: Poland and Ukraine. *Scientific Papers of Silesian University of Technology. Organization & Management / Zeszyty Naukowe Politechniki Śląskiej. Organizacji i Zarzadzanie*, *231*, 575–595. http://dx.doi.org/10.29119/1641-3466.2025.231.32

Zawada, K., Donderewicz, M., Gertner, A. & Rybak-Niedziółka, K. (2024). The impact of BIM and GIS on the efficiency of implementing construction projects. *Acta Scientiarum Polonorum. Architectura*, *23*, 358–368. https://doi.org/10.22630/ASPA.2024.23.28

KOMPLEKSOWA MODERNIZACJA BUDYNKÓW AKADEMICKICH: STUDIUM PRZYPADKU CENTRUM WODNEGO NA KAMPUSIE SGGW W WARSZAWIE

STRESZCZENIE

W artykule omówiono przegląd literatury i analizę krytyczną w odniesieniu do modernizacji budynków użyteczności publicznej o cechach podobnych do Centrum Wodnego SGGW. Niedawno opracowany projekt koncepcyjny modernizacji budynku Centrum Aktywności Wodnej SGGW w Warszawie zawierał szeroki zakres prac, dużych interwencji obejmujących przebudowę, renowację, rekonstrukcję oraz rozbudowę istniejącego budynku. Celem artykułu jest zbadanie możliwości adaptacji i optymalizacji przestrzeni zarówno wewnętrznej, jak i zewnętrznej poprzez wykorzystanie współczesnych, komputerowo wspomaganych metod projektowych oraz uwzględnienie aspektów rozwoju zrównoważonego. Hipoteza badawcza zakłada, że podejście holistyczne do modernizacji, integrujące różne branże i technologie, może znacząco poprawić funkcjonalność, efektywność energetyczną oraz dostępność budynku, a także przyczynić się do rozwoju otoczenia. Metoda badawcza obejmuje przegląd aktualnej literatury związanej z tematem oraz studium przypadku projektu Centrum Wodnego na kampusie SGGW w Warszawie. Wyniki analizy studium przypadku wskazują na liczne problemy związane z istniejącą infrastrukturą i możliwości poprawy poprzez wdrożenie koncepcji projektowej uwzględniającej cele rozwoju zrównoważonego (SDGs). Wnioski podkreślają potrzebę współpracy interdyscyplinarnej i kompleksowego podejścia, które bierze pod uwagę aspekty ekonomiczne, społeczne i środowiskowe podczas modernizacji budynków o złożonych funkcjach, co może przyczynić się do poprawy jakości przestrzeni i zaspokojenia potrzeb różnych grup użytkowników.

Słowa kluczowe: modernizacja kampusu, renowacja, architektura, urbanistyka, BIM, rozwój zrównoważony, SGGW

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