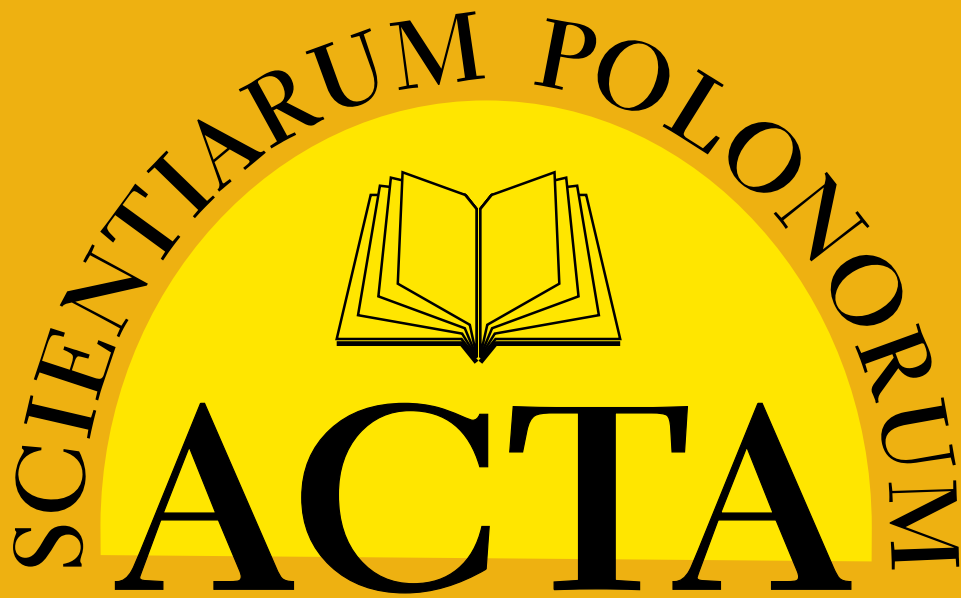


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HYDRAULIC CONDUCTIVITY TENSOR OF ANISOTROPIC SOILS: THE IMPACT ON SEEPAGE FLOW

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ABSTRACT

Natural or artificial changes in soil stratigraphic-plane (i.e., the deposition of soil and sediments into distinct layers) orientation can cause variations in hydraulic conductivity in different directions. Hydraulic conductivity must, therefore, be considered – in this case – as a nondiagonal, full tensor to appropriately represent the effect of the orientation of soil stratigraphic planes on the seepage flow pattern. This paper introduces the derivation of the formula for the three-dimensional nondiagonal hydraulic conductivity full tensor calculation in terms of azimuth and vertical angles. Furthermore, two-dimensional numerical simulations of the seepage flow beneath a concrete dam are presented to demonstrate the need to account for the nondiagonal elements of the hydraulic conductivity tensor in anisotropic soils of varying degrees of stratigraphic tilt with respect to the coordinate system.

Keywords: full tensor, hydraulic conductivity, seepage flow, soil stratigraphy, numerical simulation

INTRODUCTION

Particle orientation, compaction, illuviation and sedimentation are some soil-forming processes that can cause anisotropy in any soil (Assouline & Or, 2006; Peng, 2011). Certain natural soils possess substantial anisotropy, resulting in significant variations in their mechanical or physical characteristics in various directions. This tendency is especially noticeable in clayey soils compared to other soil types (Nguyen, Rahman & Karim, 2023). Anisotropic soils may exhibit varying transport characteristics depending on the direction of principal flow and directional hydraulic conductivity. Therefore, analysis of seepage flow through anisotropic soils might necessitate tensorial representation instead of the scalar values of hydraulic conductivity observed in isotropic soils (Assouline & Or, 2006). In anisotropic soils, the permeability of the porous medium in various directions is described by the hydraulic conductivity tensor, a matrix that depends on the flow direction and soil stratigraphy – the deposition of soil and sediments into distinct layers. The hydraulic conductivity tensor has conventionally been regarded as diagonal, which signifies that the permeability remains unaffected by the flow direction. This assumption, nevertheless, might not apply to anisotropic soil – a medium in which permeability can vary substantially in various directions – where the principal directions of hydraulic conductivity differ from the system of coordinates used for flow simulation. One instance of this is the fluid-flow equations utilised to model numerous commercial reservoirs (Ertekin, Abou-Kassem & King, 2001; Fanchi, 2005). These equations operate under the supposition that nondiagonal elements of the tensor can be disregarded, leading to

inaccurate flow calculations (Fanchi, 2008). Thus, Fanchi (2008) introduced a formula that enabled the precise computation of a two-dimensional full-hydraulic conductivity tensor, including nondiagonal components, at any rotation angle in a plane. In a subsequent study, Alam and Farid (2023) derived and utilised a similar formula to conduct numerical simulations of seepage in unsaturated soil. They investigated multiple scenarios using two-dimensional models and demonstrated that neglecting nondiagonal factors leads to erroneous seepage flows. Nonetheless, a three-dimensional model is needed to simulate more realistic circumstances, necessitating the development of a formula for the three-dimensional nondiagonal hydraulic conductivity full tensor, subject to the soil stratigraphic planes' tilt angle.

This paper presents a novel set of formulas to compute the diagonal and nondiagonal components of the three-dimensional hydraulic conductivity full tensor. Furthermore, this study employs two-dimensional numerical simulations to examine the necessity of incorporating the full-hydraulic conductivity tensor when simulating seepage flow beneath a concrete dam, considering the varying degrees of stratigraphic inclination.

BACKGROUND

Darcy's law

If v_x , v_y and v_z are the components of Darcy's velocity ($\vec{v}$) – which represents the discharge velocity of groundwater flow in X, Y and Z directions, respectively – Darcy's law in the case of anisotropic soil takes the following form:

$$\vec{v} = -\underline{k}\vec{\nabla}h, \quad (1)$$

which can be rewritten in the matrix form as follows:

$$\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix} = - \begin{bmatrix} k_{xx} & k_{xy} & k_{xz} \\ k_{yx} & k_{yy} & k_{yz} \\ k_{zx} & k_{zy} & k_{zz} \end{bmatrix} \begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{bmatrix} h, \quad (2)$$

where:

h – total (hydraulic) head,

k_{xx} , k_{yy} , k_{zz} – diagonal elements,

k_{xy} , k_{xz} , k_{yx} , k_{yz} , k_{zx} , k_{zy} – nondiagonal elements of hydraulic conductivity tensor $\underline{k}$; the nondiagonal elements of $\underline{k}$ are symmetrical.

Seepage

In terms of the specific/elastic capacity (i.e., retention) of water (m_v) and temporal variations of the hydraulic head (h) for transient seepage equation (Fredlund & Rahardjo, 1993; Genetti Jr, 1999) can be written as follows:

$$\vec{\nabla}\vec{v} = -\frac{\partial \theta}{\partial t}, \quad (3)$$

where:

θ – volumetric water content.

For unsaturated soils with constant porosity temporal, the variations of θ , $(\frac{\partial \theta}{\partial t})$ can be written as $m_v \frac{\partial h}{\partial t}$, where m_v is the slope of the soil water-retention characteristics curve (SWRC). For the purpose of this paper, the SWRC is approximated to a two-segment polynomial with the two values for its slope, $m_v \approx 0.001 \text{ m}^{-1}$ for unsaturated soils and $m_v \approx 0.00001 \text{ m}^{-1}$ for saturated soils.

DERIVATION OF HYDRAULIC CONDUCTIVITY TENSOR

In general, the tensor $\underline{k}$ has three categories of major (k_1), intermediate (k_2) and minor (k_3) principal hydraulic conductivity scalar values, where k_3 is normal and k_1 and k_2 are aligned within the soil stratigraphic plane. However, if there is a tilt in the stratigraphic planes due to natural deposition (e.g., tectonic plate movements) or human activity (e.g., tillage and field traffic), (Pulido-Moncada et al., 2021), the elements of $\underline{k}$ that are not on the diagonal need to be taken into account (i.e., will be non-zero). Nevertheless, due to the mesoscale axisymmetry of the soil, typically, the equality of k_1 and k_2 exists within the stratigraphic planes. When analysing seepage in an orthogonal coordinate system aligned with the three principal orientations of the tensor (such as horizontal stratigraphic and XY planes), the tensor is diagonal; otherwise, the hydraulic conductivity tensor $\underline{k}$ will be nondiagonal.

Two-dimensional hydraulic conductivity tensor

In a two-dimensional system of coordinates XZ and the stratigraphic plane with a positive slope α (i.e., the tilt angle is above X axis), the components of the hydraulic conductivity tensor $\underline{k}$ (k_{xx} , k_{zz} , k_{xz} , k_{zx}) are computed in terms of k_1 and k_3 as follows:

$$k_{xx} = \left(\frac{k_1 + k_3}{2} \right) + \left(\frac{k_1 - k_3}{2} \right) \cos 2\alpha, \quad (4a)$$

$$k_{xz} = k_{zx} = \left(\frac{k_1 - k_3}{2} \right) \sin 2\alpha, \quad (4b)$$

$$k_{zz} = \left(\frac{k_1 + k_3}{2} \right) - \left(\frac{k_1 - k_3}{2} \right) \cos 2\alpha. \quad (4c)$$

Derivation of three-dimensional hydraulic conductivity tensor

In the case of the three-dimensional system of coordinates XYZ, Darcy's velocity equation represented by Eq. (2) can be rewritten as follows:

$$v_x = k_{xx} g_x + k_{xy} g_y + k_{xz} g_z, \quad (5a)$$

$$v_y = k_{yx} g_x + k_{yy} g_y + k_{yz} g_z, \quad (5b)$$

$$v_z = k_{zx} g_x + k_{zy} g_y + k_{zz} g_z, \quad (5c)$$

where:

$$g_x = -\frac{\partial h}{\partial x}, g_y = -\frac{\partial h}{\partial y} \text{ and } g_z = -\frac{\partial h}{\partial z}.$$

Suppose orthogonal unit vectors $\vec{a}_1$, $\vec{a}_2$ and $\vec{a}_3$ and velocity vectors $\vec{v}_1$, $\vec{v}_2$ and $\vec{v}_3$ are in the orientation of k_1 , k_2 and k_3 , Darcy's velocity $\vec{v}$ can then also take the following form:

$$\vec{v} = v_1\vec{a}_1 + v_2\vec{a}_2 + v_3\vec{a}_3, \quad (6)$$

where:

$$\vec{a}_1 = a_{1x}\hat{i} + a_{1y}\hat{j} + a_{1z}\hat{k}, \vec{a}_2 = a_{2x}\hat{i} + a_{2y}\hat{j} + a_{2z}\hat{k} \text{ and } \vec{a}_3 = a_{3x}\hat{i} + a_{3y}\hat{j} + a_{3z}\hat{k},$$

$\hat{i}, \hat{j}, \hat{k}$ – unit vectors along the X, Y and Z axes.

If the positive values of g_x , g_y and g_z are projected on the k_1 , k_2 and k_3 axes, then the flow velocity $\vec{v}_1$ along the 1, 2 and 3 directions can be simplified as follows.

$$v_1 = (v_1)_{g_x} + (v_1)_{g_y} + (v_1)_{g_z}, \quad (7)$$

where:

$$(v_1)_{g_x} = [(g_x\hat{i}) \cdot \vec{a}_1]k_1 = [(g_x\hat{i}) \cdot (a_{1x}\hat{i} + a_{1y}\hat{j} + a_{1z}\hat{k})]k_1 = g_x a_{1x} k_1, \quad (8a)$$

$$(v_1)_{g_y} = [(g_y\hat{j}) \cdot \vec{a}_1]k_1 = [(g_y\hat{j}) \cdot (a_{1x}\hat{i} + a_{1y}\hat{j} + a_{1z}\hat{k})]k_1 = g_y a_{1y} k_1, \quad (8b)$$

$$(v_1)_{g_z} = [(g_z\hat{k}) \cdot \vec{a}_1]k_1 = [(g_z\hat{k}) \cdot (a_{1x}\hat{i} + a_{1y}\hat{j} + a_{1z}\hat{k})]k_1 = g_z a_{1z} k_1. \quad (8c)$$

Substitution of these values on Eq. (7) reduces to the following form:

$$v_1 = (g_x a_{1x} + g_y a_{1y} + g_z a_{1z})k_1. \quad (9)$$

In a similar manner:

$$v_2 = (g_x a_{2x} + g_y a_{2y} + g_z a_{2z})k_2, \quad (10)$$

$$v_3 = (g_x a_{3x} + g_y a_{3y} + g_z a_{3z})k_3. \quad (11)$$

Employing Eq. (9) through Eq. (11) on Eq. (6) and rearranging results as follows:

$$\begin{aligned} \vec{v} = & [(g_x a_{1x}^2 + g_y a_{1x} a_{1y} + g_z a_{1x} a_{1z})k_1 + (g_x a_{2x}^2 + g_y a_{2x} a_{2y} + g_z a_{2x} a_{2z})k_2 + (g_x a_{3x}^2 + \\ & + g_y a_{3x} a_{3y} + g_z a_{3x} a_{3z})k_3]\hat{i} + [(g_x a_{1y} a_{1x} + g_y a_{1y}^2 + g_z a_{1y} a_{1z})k_1 + (g_x a_{2y} a_{2x} + g_y a_{2y}^2 + \\ & + g_z a_{2y} a_{2z})k_2 + (g_x a_{3y} a_{3x} + g_y a_{3y}^2 + g_z a_{3y} a_{3z})k_3]\hat{j} + [(g_x a_{1z} a_{1x} + g_y a_{1z} a_{1y} + g_z a_{1z}^2)k_1 + \\ & + (g_x a_{2z} a_{2x} + g_y a_{2z} a_{2y} + g_z a_{2z}^2)k_2 + (g_x a_{3z} a_{3x} + g_y a_{3z} a_{3y} + g_z a_{3z}^2)k_3]\hat{k}. \end{aligned} \quad (12)$$

Comparing Eq. (12) with $\vec{v} = v_x \hat{i} + v_y \hat{j} + v_z \hat{k}$ results in:

$$v_x = (a_{1x}^2 k_1 + a_{2x}^2 k_2 + a_{3x}^2 k_3) g_x + (a_{1x} a_{1y} k_1 + a_{2x} a_{2y} k_2 + a_{3x} a_{3y} k_3) g_y + (a_{1x} a_{1z} k_1 + a_{2x} a_{2z} k_2 + a_{3x} a_{3z} k_3) g_z, \quad (13a)$$

$$v_y = (a_{1y} a_{1x} k_1 + a_{2y} a_{2x} k_2 + a_{3y} a_{3x} k_3) g_x + (a_{1y}^2 k_1 + a_{2y}^2 k_2 + a_{3y}^2 k_3) g_y + (a_{1y} a_{1z} k_1 + a_{2y} a_{2z} k_2 + a_{3y} a_{3z} k_3) g_z, \quad (13b)$$

$$v_z = (a_{1z} a_{1x} k_1 + a_{2z} a_{2x} k_2 + a_{3z} a_{3x} k_3) g_x + (a_{1z} a_{1y} k_1 + a_{2z} a_{2y} k_2 + a_{3z} a_{3y} k_3) g_y + (a_{1z}^2 k_1 + a_{2z}^2 k_2 + a_{3z}^2 k_3) g_z. \quad (13c)$$

Equating the left-hand sides of Eq. (5) with Eq. (13) provides the diagonal and nondiagonal components of the hydraulic conductivity tensor $\underline{k}$ in terms of k_1 , k_2 and k_3 as follows:

$$\left. \begin{aligned} k_{xx} &= a_{1x}^2 k_1 + a_{2x}^2 k_2 + a_{3x}^2 k_3 \\ k_{yy} &= a_{1y}^2 k_1 + a_{2y}^2 k_2 + a_{3y}^2 k_3 \\ k_{zz} &= a_{1z}^2 k_1 + a_{2z}^2 k_2 + a_{3z}^2 k_3 \\ k_{xy} &= k_{yx} = a_{1x} a_{1y} k_1 + a_{2x} a_{2y} k_2 + a_{3x} a_{3y} k_3 \\ k_{yz} &= k_{zy} = a_{1y} a_{1z} k_1 + a_{2y} a_{2z} k_2 + a_{3y} a_{3z} k_3 \\ k_{zx} &= k_{xz} = a_{1z} a_{1x} k_1 + a_{2z} a_{2x} k_2 + a_{3z} a_{3x} k_3 \end{aligned} \right\} \quad (14)$$

The unit vectors $\vec{a}_1$, $\vec{a}_2$ and $\vec{a}_3$ are orthogonal to each other and $\vec{a}_3$ is normal to the soil stratigraphic plane (Fig. 1). The figure shows the projection of $\vec{a}_3$ and $\vec{a}_1$ on the X, Y and Z axes, respectively – from which the unit vectors $\vec{a}_1$, $\vec{a}_2$ and $\vec{a}_3$ can be expressed in terms of the vertical angle and azimuth.

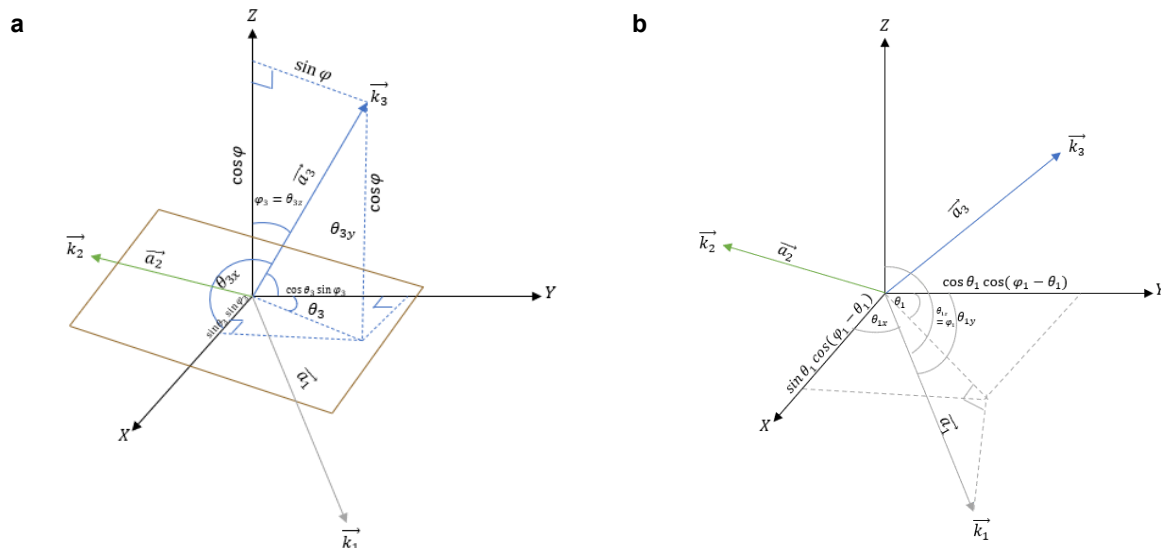


Fig. 1. Projections: a – $\vec{a}_3$ on X, Y and Z axes; b – $\vec{a}_1$ on X, Y and Z axes

Source: authors' compilation.

Assuming unit vectors $\vec{a}_1$, $\vec{a}_2$ and $\vec{a}_3$ can be expressed as follows:

$$\vec{a}_1 = a_{1x}\hat{i} + a_{1y}\hat{j} + a_{1z}\hat{k} = \cos \theta_{1x} \hat{i} + \cos \theta_{1y} \hat{j} + \cos \theta_{1z} \hat{k}, \quad (15a)$$

$$\vec{a}_2 = a_{2x}\hat{i} + a_{2y}\hat{j} + a_{2z}\hat{k} = \cos \theta_{2x} \hat{i} + \cos \theta_{2y} \hat{j} + \cos \theta_{2z} \hat{k}, \quad (15b)$$

$$\vec{a}_3 = a_{3x}\hat{i} + a_{3y}\hat{j} + a_{3z}\hat{k} = \cos \theta_{3x} \hat{i} + \cos \theta_{3y} \hat{j} + \cos \theta_{3z} \hat{k}. \quad (15c)$$

From Figure 1a, it can be concluded that:

$$\vec{a}_3 = \cos \theta_{3x} \hat{i} + \cos \theta_{3y} \hat{j} + \cos \theta_{3z} \hat{k} \Rightarrow \vec{a}_3 = \sin \theta_3 \sin \varphi_3 \hat{i} + \cos \theta_3 \sin \varphi_3 \hat{j} + \cos \varphi_3 \hat{k}. \quad (16)$$

For any given vertical angle (VA), where $\varphi_3 = (90^\circ - VA)$; and azimuth A_{z3} , where $\theta_3 = A_{z3}$, $\vec{a}_3$ can be found from Eq. (16).

Similarly, from Figure 1b, it can be deduced that:

$$\vec{a}_1 = \cos \theta_{1x} \hat{i} + \cos \theta_{1y} \hat{j} + \cos \theta_{1z} \hat{k} \Rightarrow \vec{a}_1 = \sin \theta_1 \cos(\varphi_1 - \theta_1) \hat{i} + \cos \theta_1 \cos(\varphi_1 - \theta_1) \hat{j} + \cos \varphi_1 \hat{k}. \quad (17)$$

Since $\vec{a}_1$ and $\vec{a}_3$ are orthogonal, their dot product is zero (i.e., $\vec{a}_1 \cdot \vec{a}_3 = 0$), which is essentially the dot product of Eq. (16) and (17) results in the following form.

$$\sin \theta_1 \cos(\varphi_1 - \theta_1) \sin \theta_3 \sin \varphi_3 + \cos \theta_1 \cos(\varphi_1 - \theta_1) \cos \theta_3 \sin \varphi_3 + \cos \varphi_1 \cos \varphi_3 = 0. \quad (18)$$

For a given azimuth A_{z1} , where $\theta_1 = A_{z1}$, the value of φ_1 , $0 < \varphi_1 < \pi$ can be found from Eq. (18) to obtain $\vec{a}_1$ from Eq. (17).

Again, since $\vec{a}_2$ is orthogonal to both $\vec{a}_1$ and $\vec{a}_3$; therefore, $\vec{a}_2 = \vec{a}_1 \times \vec{a}_3$. Thus, the cross-product of Eq. (16) and Eq. (17) produces $\vec{a}_2$ as follows:

$$\vec{a}_2 = (\cos \theta_1 \cos(\varphi_1 - \theta_1) \cos \varphi_3 - \cos \varphi_1 \cos \theta_3 \sin \varphi_3) \hat{i} + (\cos \varphi_1 \sin \theta_3 \sin \varphi_3 - \sin \theta_1 \cos(\varphi_1 - \theta_1) \cos \varphi_3) \hat{j} + (\sin \theta_1 \cos(\varphi_1 - \theta_1) \cos \theta_3 \sin \varphi_3 - \cos \theta_1 \cos(\varphi_1 - \theta_1) \sin \theta_3 \sin \varphi_3) \hat{k}. \quad (19)$$

Substituting Eqs (16), (17) and (19) into Eq. (14) gives the elements of the full three-dimensional hydraulic conductivity tensor $\underline{k}$ as follows:

$$k_{xx} = \sin^2 \theta_1 \cos^2(\varphi_1 - \theta_1) k_1 + (\cos \theta_1 \cos(\varphi_1 - \theta_1) \cos \varphi_3 - \cos \varphi_1 \cos \theta_3 \sin \varphi_3)^2 k_2 + \sin^2 \theta_3 \sin^2 \varphi_3 k_3, \quad (20a)$$

$$k_{yy} = \cos^2 \theta_1 \cos^2(\varphi_1 - \theta_1) k_1 + (\cos \varphi_1 \sin \theta_3 \sin \varphi_3 - \sin \theta_1 \cos(\varphi_1 - \theta_1) \cos \varphi_3)^2 k_2 + \cos^2 \theta_3 \sin^2 \varphi_3 k_3, \quad (20b)$$

$$k_{zz} = \cos^2 \varphi_1 k_1 + (\sin \theta_1 \cos(\varphi_1 - \theta_1) \cos \theta_3 \sin \varphi_3 - \cos \theta_1 \cos(\varphi_1 - \theta_1) \sin \theta_3 \sin \varphi_3)^2 k_2 + \cos^2 \varphi_3^2 k_3, \quad (20c)$$

$$k_{xy} = k_{yx} = \sin \theta_1 \cos \theta_1 \cos^2(\varphi_1 - \theta_1) k_1 + (\cos \theta_1 \cos(\varphi_1 - \theta_1) \cos \varphi_3 - \cos \varphi_1 \cos \theta_3 \sin \varphi_3)(\cos \varphi_1 \sin \theta_3 \sin \varphi_3 - \sin \theta_1 \cos(\varphi_1 - \theta_1) \cos \varphi_3) k_2 + \sin \theta_3 \sin \varphi_3 \cos \theta_3 \sin \varphi_3 k_3, \quad (20d)$$

$$k_{yz} = k_{zy} = \cos \theta_1 \cos(\varphi_1 - \theta_1) \cos \varphi_1 k_1 + (\cos \varphi_1 \sin \theta_3 \sin \varphi_3 - \sin \theta_1 \cos(\varphi_1 - \theta_1) \cos \varphi_3)(\sin \theta_1 \cos(\varphi_1 - \theta_1) \cos \theta_3 \sin \varphi_3 - \cos \theta_1 \cos(\varphi_1 - \theta_1) \sin \theta_3 \sin \varphi_3) k_2 + \cos \theta_3 \sin \varphi_3 \cos \varphi_3 k_3, \quad (20e)$$

$$k_{zx} = k_{xz} = \cos \varphi_1 \sin \theta_1 \cos(\varphi_1 - \theta_1) k_1 + (\sin \theta_1 \cos(\varphi_1 - \theta_1) \cos \theta_3 \sin \varphi_3 - \cos \theta_1 \cos(\varphi_1 - \theta_1) \sin \theta_3 \sin \varphi_3)(\cos \theta_1 \cos(\varphi_1 - \theta_1) \cos \varphi_3 - \cos \varphi_1 \cos \theta_3 \sin \varphi_3) k_2 + \cos \varphi_3 \sin \theta_3 \sin \varphi_3 k_3. \quad (20f)$$

NUMERICAL SIMULATION

Seepage flow formulation

The seepage flow under a concrete dam is simulated here to demonstrate the impact of the nondiagonal $\underline{k}$ on the tilted soil's stratigraphic planes. In this model, the upstream and downstream lakes are simulated as inlet and outlet, respectively – as schematically shown in Figure 2.

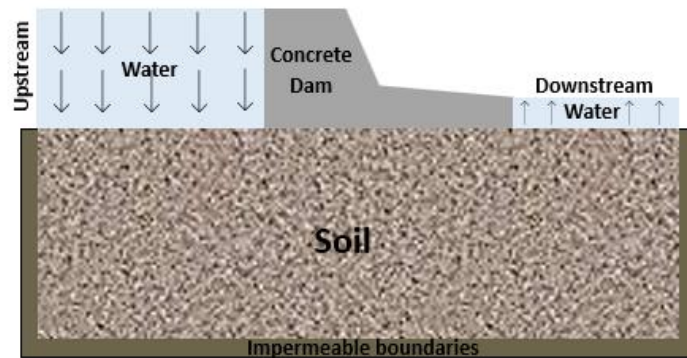


Fig. 2. Schematic of the model for an upstream (inlet) and a downstream (outlet) at the top boundary

Source: authors' compilation.

Mathematical model

The combination of Eq. (1) and Eq. (2) govern the seepage, which for a two-dimensional problem can be reduced to the following form:

$$-\left[\frac{\partial}{\partial x} \quad \frac{\partial}{\partial z}\right] \begin{bmatrix} k_{xx} & k_{xz} \\ k_{zx} & k_{zz} \end{bmatrix} \begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial z} \end{bmatrix} h = -m_v \frac{\partial h}{\partial t}, \quad (21)$$

which can be expanded as follows:

$$-\left[\frac{\partial k_{xx}}{\partial x} \frac{\partial h}{\partial x} + k_{xx} \frac{\partial^2 h}{\partial x^2} + \frac{\partial k_{xz}}{\partial x} \frac{\partial h}{\partial z} + k_{xz} \frac{\partial^2 h}{\partial x \partial z} + \frac{\partial k_{zx}}{\partial z} \frac{\partial h}{\partial x} + k_{zx} \frac{\partial^2 h}{\partial z \partial x} + \frac{\partial k_{zz}}{\partial z} \frac{\partial h}{\partial z} + k_{zz} \frac{\partial^2 h}{\partial z^2}\right] = -m_v \frac{\partial h}{\partial t}. \quad (22)$$

Finite-difference model development

A two-dimensional finite-difference numerical model was developed using the MATLAB interface, with Dirichlet boundary conditions at the upstream (inlet) and downstream (outlet) (i.e., hydraulic heads are constants (H_1 and H_2) and Neumann boundary conditions considered for the rest of the impermeable boundaries). This model is used to demonstrate that in the case of tilted soil stratigraphic planes, the full-hydraulic conductivity tensor $\underline{k}$ is required to simulate seepage flow accurately.

The linearised form of Eq. (22), discretised over a rectangular grid using the forward finite difference for first-order derivatives and central finite difference for higher-order derivatives, can be shown as:

$$\begin{aligned} & \frac{k_{xx}(i,j)}{(\Delta x)^2} h_{i,j-1}^{t_{k+1}} - \left(\frac{k_{xx}(i,j+1) - k_{xx}(i,j)}{(\Delta x)^2} + 2 \frac{k_{xx}(i,j)}{(\Delta x)^2} + \frac{k_{xz}(i,j+1) - k_{xz}(i,j)}{\Delta x \Delta z} + 2 \frac{k_{xz}(i,j)}{\Delta x \Delta z} + \frac{k_{zx}(i+1,j) - k_{zx}(i,j)}{\Delta z \Delta x} + 2 \frac{k_{zx}(i,j)}{\Delta z \Delta x} \right. \\ & + \left. \frac{k_{zz}(i+1,j) - k_{zz}(i,j)}{(\Delta z)^2} + 2 \frac{k_{zz}(i,j)}{(\Delta z)^2} + \frac{m_v(i,j)}{\Delta t} \right) h_{i,j}^{t_{k+1}} + \left(\frac{k_{xx}(i,j+1) - k_{xx}(i,j)}{(\Delta x)^2} + \frac{k_{xx}(i,j)}{(\Delta x)^2} + \frac{k_{zx}(i+1,j) - k_{zx}(i,j)}{\Delta z \Delta x} \right) h_{i,j+1}^{t_{k+1}} + \\ & + \left(\frac{k_{xz}(i,j)}{\Delta x \Delta z} + \frac{k_{zx}(i,j)}{\Delta z \Delta x} \right) h_{i-1,j-1}^{t_{k+1}} + \frac{k_{zz}(i,j)}{(\Delta z)^2} h_{i-1,j}^{t_{k+1}} + \left(\frac{k_{xz}(i,j+1) - k_{xz}(i,j)}{\Delta x \Delta z} + \frac{k_{zz}(i+1,j) - k_{zz}(i,j)}{(\Delta z)^2} + \frac{k_{zz}(i,j)}{(\Delta z)^2} \right) h_{i+1,j}^{t_{k+1}} + \\ & + \left(\frac{k_{xz}(i,j)}{\Delta x \Delta z} + \frac{k_{zx}(i,j)}{\Delta z \Delta x} \right) h_{i+1,j+1}^{t_{k+1}} = - \frac{m_v(i,j)}{\Delta t} h_{i,j}^{t_k}, \end{aligned} \quad (23)$$

where $h_{i,j}^{t_k}$ represents the hydraulic head on Row i , Column j (i.e., Node (i,j)) in the space and at time instance t_k ; $h_{i,j}^{t_{k+1}}$ is the hydraulic head at Node (i,j) at time t_{k+1} and so on. For this model, in the case of unsaturated soil – with each time step – each of the components of the $\underline{k}$ in Eq. (23) were updated using the soil water-retention formula (Alam & Farid, 2023), which introduces nonlinearity back into the equation. Thus, these nonlinear components of the $\underline{k}$ were updated using a modified iterated Crank–Nicholson scheme (Tran & Liu, 2016) until they converged to their optimal value.

Simulation result and discussion

The subsequent conditions were applied for every scenario shown in Figures 3–5. The soil is initially unsaturated, with a total head of $h = 0$, indicating capillary rise and suction at all elevations. All other soil boundaries, apart from inlets and outlets, are impermeable. The assumed dimensions of the soil are 30 m for the horizontal length (L) and 10 m for the vertical length – thickness (T). The initial hydraulic heads at the inlet is $H_1 = 50$ m, and at the outlet, $H_2 = 10$ m. The seepage flow is simulated through an anisotropic soil with a major principal hydraulic conductivity value of $k_1 = 5.5 \times 10^{-2} \text{ m}\cdot\text{s}^{-1}$ and a minor principal hydraulic conductivity value of $k_3 = 1.5 \times 10^{-2} \text{ m}\cdot\text{s}^{-1}$ of the hydraulic conductivity tensor $\underline{k}$. Each scenario was examined for 5,000 s at a time step of $\Delta t = 20$ s.

The model was tested for various additional circumstances; however, only a few are shown below. In all of the following scenarios, a tilt is present, resulting in estimated values of the diagonal components of the hydraulic conductivity tensor as $k_{xx} = 5.03 \times 10^{-2} \text{ m}\cdot\text{s}^{-1} < k_1$ and $k_{zz} = 1.97 \times 10^{-2} \text{ m}\cdot\text{s}^{-1} > k_3$. In Figure 3, the first scenario, however, inaccurately depicts a symmetric seepage flow pattern identical for both downward ($\alpha = -20^\circ$) and upward ($\alpha = 20^\circ$) tilts due to erroneous assumption of the values of the nondiagonal components of the tensor $\underline{k}$ as $k_{xz} = k_{zx} = 0$. However, for $\alpha = -20^\circ$ and $\alpha = 20^\circ$, Figures 4 and 5 exhibit accurate seepage flow patterns, with calculated values for the nondiagonal components as $k_{xz} = k_{zx} = -1.29 \times 10^{-2} \text{ m}\cdot\text{s}^{-1}$ and $k_{xz} = k_{zx} = 1.29 \times 10^{-2} \text{ m}\cdot\text{s}^{-1}$, consequently.

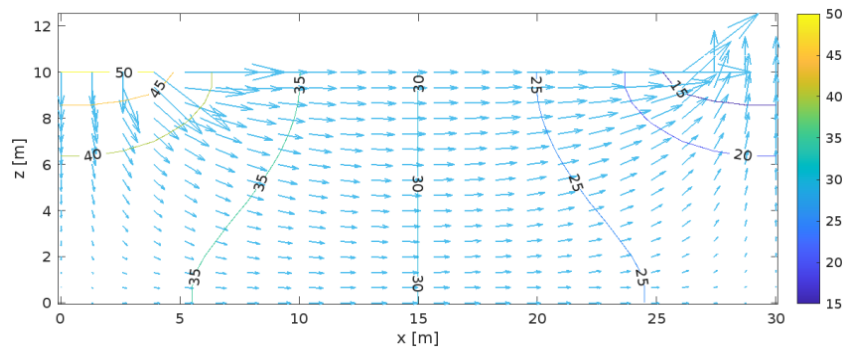


Fig. 3. Equipotential lines and flow velocity vectors considering a forced diagonalised (erroneous approximation) hydraulic conductivity tensor (i.e., $k_{xz} = k_{zx} = 0$), which has produced the same results for tilts (between the soil stratigraphic plane and the horizontal X axis) of $\alpha = 20^\circ$ (i.e., above the horizon) and $\alpha = -20^\circ$ (i.e., below the horizon)

Source: authors' compilation.

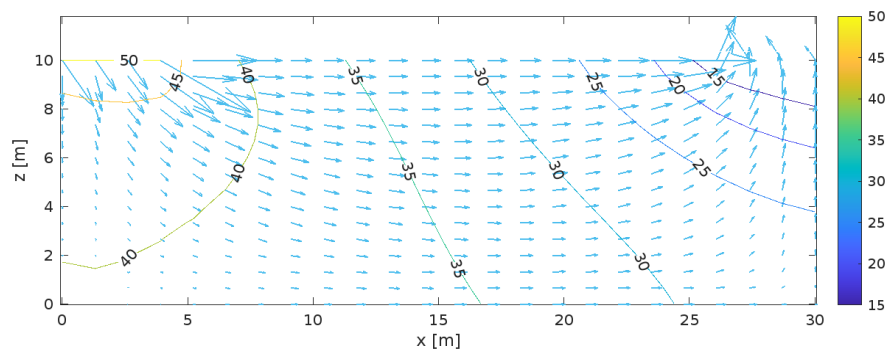


Fig. 4. Equipotential lines and flow velocity vectors for nondiagonalised (correct approximation) hydraulic conductivity tensor (i.e., $k_{xz} = k_{zx} \neq 0$) for a tilt between the soil stratigraphic plane and horizontal X-axis with slope $\alpha = -20^\circ$ (i.e., below the horizon)

Source: authors' compilation.

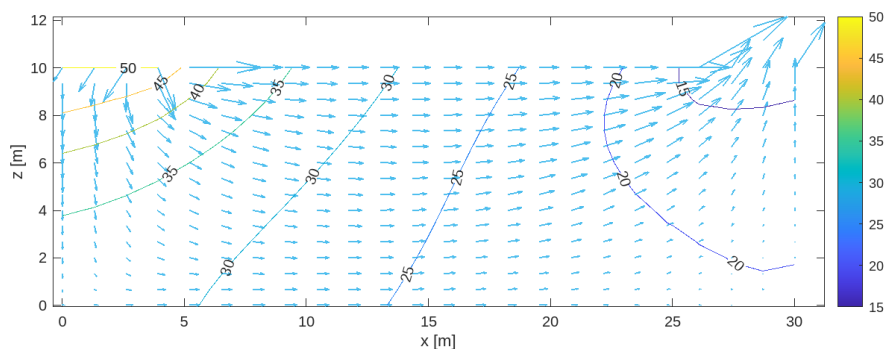


Fig. 5. Equipotential lines and flow velocity vectors for non-diagonalised (correct approximation) hydraulic conductivity tensor (i.e., $k_{xz} = k_{zx} \neq 0$) for a tilt between the soil stratigraphic plane and the horizontal X-axis with slope $\alpha = 20^\circ$ (i.e., above the horizon)

Source: authors' compilation.

CONCLUSIONS

This study introduces formulas to compute three-dimensional full-hydraulic conductivity tensor components. Furthermore, seepage flow under a concrete dam is simulated using a two-dimensional finite-difference numerical model to illustrate the failure of ignoring the nondiagonal components of the hydraulic conductivity tensor inaccurately finding seepage flow for scenarios that involve tilted soil stratigraphic planes. Although the provided formula analytically calculates both diagonal and nondiagonal elements of the three-dimensional full-hydraulic conductivity tensor, there is still a need to develop a three-dimensional model for simulating seepage flow that can employ the three-dimensional full-hydraulic conductivity tensor to replicate realistic circumstances, enabling an exhaustive evaluation of the formula's precision.

Authors' contributions

Conceptualisation: M.A. and A.F.; methodology: M.A.; validation: A.F. and Y.Y.; formal analysis: M.A. and A.F.; investigation: M.A.; resources: M.A. and A.F.; data curation: M.A. and A.F.; writing – original draft preparation: M.A.; writing – review and editing: A.F.; visualisation: M.A.; supervision: A.F.; project administration: A.F.; funding acquisition: A.F.

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

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WYZNACZANIE TENSORA PEŁNEGO PRZEWODNICTWA HYDRAULICZNEGO GRUNTU ANIZOTROPOWEGO: WPŁYW NA PRZEPŁYW WYCIĘKÓW POD ZAPORĄ BETONOWĄ

STRESZCZENIE

Naturalne lub sztuczne zmiany w orientacji płaszczyzny stratygraficznej gleby (tj. osadzanie się gleby i osadów w odrębnych warstwach) mogą powodować zmiany przewodności hydraulicznej w zależności od kierunku pomiaru. Z tego powodu należy uwzględnić w tym przypadku przewodność hydrauliczną jako niediagonalny pełny tensor, aby odpowiednio przedstawić wpływ orientacji płaszczyzn stratygraficznych gleby na wzór przepływu infiltracyjnego. W niniejszej pracy przedstawiono wzór na trójwymiarowe niediagonalne obliczenie tensora pełnego przewodnictwa hydraulicznego w aspekcie azymutu i kąta pionowego. Ponadto przedstawiono symulacje numeryczne dwuwymiarowych przepływów wyciekowych pod betonową zaporą, aby wykazać potrzebę uwzględnienia pełnego tensora przewodności hydraulicznej dla różnych stopni nachylenia stratygraficznego względem układu współrzędnych.

Słowa kluczowe: pełny tensor, przewodność hydrauliczna, przepływ przesiąkający, stratygrafia gleby, model numeryczny

FOSTERING SUSTAINABLE URBAN DEVELOPMENT: INTEGRATING SCHOOL AREAS TO SUPPORT THE CITY'S GREEN-BLUE INFRASTRUCTURE

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ABSTRACT

The effects of the climate crisis disproportionately affect people living in densely populated urban areas, presenting a major challenge for the 21st century. Urban administrators face a significant challenge in implementing sustainable development goals into practice, especially within the constraints of the current infrastructure. This paper evaluates how school zones – characterised by a significant amount of biologically active areas – are integrated into the city's infrastructure to support the multiple uses of natural resources that improve urban living standards. A comprehensive analysis of current legislation, a review of the scientific literature, and a case study of selected schoolyards and school campuses, and renovations of these types of sites over the past decade focus on the evolution of school grounds and the formulation of green spaces and green-blue infrastructure. The paper's conclusions outline the possibilities embedded in the evolution of schoolyards in the pursuit of sustainable development functioning and a list of the potentialities of urban ecological initiatives.

Keywords: green-blue infrastructure, schools, smart city, sustainability

INTRODUCTION

The United Nations (UN) estimates that over half of the world's population currently resides in urban areas, a particularly pronounced trend in developing countries. By 2050, the number of people living in cities is expected to increase to 68% (Allam, Bibri, Chabaud & Moreno, 2022). As a result, there is a growing need for intelligent infrastructure to support human functioning in densely populated areas. Today's accelerating urban development must be supported by sustainable measures to minimise the consumption of natural resources and to change the negative impact on the surrounding environment. The increasing awareness of designers and users contributes to non-anthropocentric issues and bio-polises (Kleszcz, 2021). The new approach to sustainable cities treats them as integrated systems like smart cities (Allam et al., 2022). The increasing population in urban areas requires expanding living space for education and technical infrastructure such as roads and utilities to ensure the city's viability and the residents' comfort. Sustainable development has three pillars: social, economic, and environmental (Dalampira & Nastis, 2020; Jeronen, 2020). The presence of nature in the city is not only an important factor for water retention, temperature regulation, and air purification.

Residents also need to relax, rest, and enjoy recreation (Gu & Zheng, 2010; Shah et al., 2021). Due to increasing urbanisation, green spaces in cities are becoming scarce (Brahimi, Benabbas, Altan, Nocera & Costanzo, 2023), often a privilege of wealthy neighbourhoods (Shah et al., 2021). Modern urban development involves green-blue infrastructure (GBI) to serve the city and its residents regardless of ownership status. In this approach, green spaces become a focal point of the city's purification grid, and the search for these spaces, also associated with closed functions, is increasingly necessary. School campuses are among the areas worthy of attention due to the usually significant amount of green space adjacent to them (Brandli, Salvia, da Rocha, Mazutti & Reginatto, 2020; Zhu, Zhu & Dewancker, 2020). The article analyses the possibilities and ways of using GBI on school campuses and related green spaces. This study analyses whether green spaces on school grounds can be designed as part of a GBI that forms a local green enclave. The selected literature on the subject is presented further, showing the state of research on the analysed problem, followed by an analysis of the possibility of applying GBI in contemporary schools in the world and in Poland. The article concludes with a roadmap for good solutions to support GBI in educational institutions.

LITERATURE REVIEW

Green-blue infrastructure

The rapid development of civilisation and human expansion has led to the deterioration of natural resources and the quality of human life (Mittal & Ravi, 2015; Ahmad et al., 2020; Nathaniel, Nwulu & Bekun, 2021). Constant exposure to poor-quality air and water and increasingly demanding access to the elements of nature are leading to a deterioration in the condition of both nature and people. To prevent this, governments, international organisations, and grassroots initiatives by residents are trying to reverse how people use natural resources. An example of this is following sustainable development so as not to harm but also not to live at the expense of future generations. One of the sustainable development goals (SDGs), adopted at the UN Summit in September 2015 includes a movement towards greening, with the possibility of citizens participation (Vidal, Barros & Maia, 2020; Moczek, Voigt-Heucke, Mortega, Fabó Cartas & Knobloch, 2021; Goel & Vishnoi, 2022; Lombardía & Gómez-Villarino, 2023). Goals 3, 11, 13 and 15 address health and well-being, sustainable cities and communities, action on climate change, and the protection of life on land (Omer & Noguchi, 2020; Xu et al., 2020). The need to integrate new solutions into the urban fabric assumes that the GBI's inherent multifunctionality will provide social benefits while supporting biodiversity conservation and climate change mitigation and adaptation goals. However, a limitation of this approach is still the lack of clear guidelines and the exact conditions that would prevail for social benefits to accrue from applying GBI strategies for different ethnic and age groups (Andersson et al., 2022). Nevertheless, there is an apparent push to introduce the GBI as a key link in urban planning focused on the SDGs goals.

Since no clear legal interpretation of the GBI exists, many different interpretations are emerging. Some understand it as a system of different green and blue areas. Others see GBI as a planning strategy for networks of natural and natural-based, semi-natural or protected areas with local and global impacts (Macháč, Brabec & Arnberger, 2022). Several reviews cover different aspects of GBI, including its potential as a climate change adaptation strategy, its impact on ecosystems and human health, and its role in the food-energy-water nexus (Almaaitah, Appleby, Rosenblat, Drake & Joksimovic, 2021; Shah et al., 2021). The reviews highlight the importance of GBI in mitigating urban heat, managing stormwater, and promoting sustainability and resilience in cities. While some studies highlight the benefits of integrating green-blue-grey infrastructure, others point to further research to understand the complexities associated with this integration (Ying, Zhang, Zhang & Bilan, 2022). Overall, the literature underscores the importance of GBI as a strategic planning and design tool to address urban challenges and promote sustainable development.

The role of GBI's is to improve economic, social, and environmental indicators through the multifunctional use of natural resources. The successful examples of green infrastructure (GI) in cities mitigate the urban heat island effect and create more sustainable and comfortable urban environments. Such infrastructure appears to be a socially acceptable solution that can be easily implemented in school park areas (Corrigan, 2023):

- Green roofs: The adoption of green roofs has been effective in combating urban heat islands by providing natural insulation, reducing surface temperatures, and promoting evaporative cooling.
- Tree canopies: Planting and maintaining tree canopies in urban areas has proven to be an effective strategy for shading and reducing surface temperatures, thereby mitigating the urban heat island effect.
- Rain gardens and bioswales: These GI features help manage stormwater, improve water quality, and help reduce the urban heat island effect by promoting evaporative cooling and creating more thermally balanced urban environments.
- Parks and green spaces: Creating parks, gardens, and other green spaces within cities has successfully reduced the urban heat island effect by providing shade, lowering surface temperatures, and promoting evaporative cooling.

City's GI manifests itself as parks, gardens, plazas, open lawns, or forests. At the same time, blue infrastructure (BI) consists of rivers, river tributaries and canals, retention ponds, basins, reservoirs, bioretention ditches, infiltration ditches, and rain gardens. The GBI connections are most often green-blue corridors. Creating interconnected networks of water bodies and green spaces, known as green-blue corridors, has proven successful in promoting biodiversity, improving air quality, and creating more resilient and livable urban environments. This contrasts grey infrastructure, which consists of roads, paved riverbanks, parking lots and other impervious surfaces (Macháč et al., 2022). Surveys show that residents value green spaces and, especially, the presence of trees (Trzaskowska, Renda, Adamiec & Kułak, 2023), a sustainable development strategy. The GBI is one of the best practices in local systems management for building urban resilience.

Smarter cities

The idea of smart cities based on smart solutions is to create infrastructural and technologically connected urban areas (Kumar, Singh, Gupta & Madaan, 2020; Šurdonja, Giuffrè & Deluka-Tibljaš, 2020). The concept was defined in the 20th century as the virtual city began to merge with reality. Smart cities are designed to provide a high quality of life, efficient management of resources and progressiveness. It considers the basic pillars: smart people, smart economy, smart governance smart mobility, smart environment. Smart city focuses on the entire urban system, integrating all subsystems, and is designed to improve safety, support urban development, and counter natural disasters (Jiang, 2020; Kutty, Abdella, Kucukvar, Onat & Bulu, 2020). The amount of data collected for these purposes, supported by Internet of Things (IoT) systems, can make predicting and proactively responding to weather phenomena possible. Natural resources such as parks and waterways are just part of the infrastructure needed for sustainable development. When these resources are well managed, cities will become smarter.

Urban infrastructure areas are primarily grey infrastructure. They are divided according to their main functions: security, transportation, communication, lighting, water, and wastewater infrastructure and heating. Smart city combines many different systems of the urban landscape. One of them could be ecosystem services (ES). The key to success is a systems approach considering the individual context and situation. The GBI helps mitigate the broader impacts of challenges such as climate change, outdoor recreation, and social activity spaces. On the other hand, there is evidence of problems with the equitable availability of GBI and its benefits. Harnessing the potential of GBI as a systems approach in ES, combined with the need for new legal and ownership regulations (Andersson et al., 2019).

Smart solutions such as advanced sensor technologies, data analytics, and IoT can improve the efficiency and effectiveness of green-blue infrastructure. They enable real-time monitoring, informed decision-making, and adaptive management for long-term urban development. Nature-based strategies include restoring and maintaining natural bio-networks in urban environments. These measures provide numerous environmental benefits and help adapt to and mitigate climate change (Hassan, Shahbaz & Gallardo Lopez, 2023).

Since 2010, New York City has implemented a GI Plan using a geographic information system (GIS) that enables the collection, management, analysis, and mapping of various spatial data types. As part of the plan, GIS is being used to monitor project progress and manage GI resources. In addition, a GI co-benefit calculator has been made available. This publicly available web-based tool allows designers and planners to identify different types of GI and their parameters to estimate costs and assess environmental, social and economic aspects. The tool is also publicly available (Nowak, 2023).

Researchers' interest in the GBI topic has increased since 2018 and this significantly growing trend continues until March 2021 (de Macedo, Barda Picavet, Puppim de Oliveira & Shih, 2021; Veerkamp et al., 2021; Janiszek & Krzysztofik, 2023), with a large lead in the United Kingdom (UK). After that time, interest is still seen, but the topic develops slower. Poland ranks fourth behind Australia and Germany. Interest in this strategy is emerging mainly in developing countries, but more and more countries are trying to implement GBI solutions (Chandwani, Singh, Satpute & Dabir, 2021).

In Pakistan, federal, provincial, and local authorities launched the Clean and Green Pakistan Strategy (CGPS) program in 2019 to promote green growth (GG). Among other things, the strategy relied on the involvement of educational institutions. Promotion was done through research and encouraging young people to develop innovative ideas (Mumtaz, 2021). Studies show that young people in Japan know the role of GI (Tanaka, Mao & Furuya, 2022), which is also related to the *mottainai* approach (Jakimiuk et al., 2023).

Green-blue infrastructure in school areas

The city comprises people, and the next generation of innovators is in schools today. Improving educational institutions' operations also influences young people's sense of responsibility for their surroundings, not only those who will graduate in the future with majors related to the construction sector. The following aspects can be considered in education while supporting the GBI of urban structures.

Water

Water at schools comes from canals, rivers, or ponds. They can also be rain gardens, retention ponds, or cisterns. This prevents drought and protects against flooding. Elements of blue infrastructure can support the GBI system in areas where flooding is possible. As global warming intensifies, storms are becoming increasingly violent. Satellite data spanning nearly four decades has shown an increase in the frequency of intense hurricanes, cyclones, and typhoons (Kornei, 2020; Alimonti, Mariani, Prodi & Ricci, 2022). Cities struggle to handle such large amounts of water at once through its sewage system, resulting in flooding (Dąbrowska et al., 2023). This is often due to the outdated design of sewage systems, as seen in Warsaw, where the system was built in the 1960s (Sobieraj, Bryx & Metelski, 2022). However, technologies exist to combine sanitary and storm sewer systems into a combined sewer system. However, rebuilding the existing infrastructure is very costly and incompatible with the principles of sustainable development. Cities are considering such solutions for major infrastructure renovations and for new projects (Qin, 2020).

Trees and perennials

Older trees contribute much more to the environment; they produce more oxygen than newly planted trees. Therefore, their cutting should be kept to a minimum. Native and non-toxic species should be planted. Trees provide shelter for birds that nest in their crowns. Trees regulate the local microclimate, provide shade on

hot days, and collect water, such as willow. European folklore and internet sources suggest that some trees repel insects, including mosquitoes. Many plants are believed to have mosquito-repelling properties, but this requires further investigation in the European climate. Mosquitoes require stagnant water for breeding. It is believed that cones from the black alder tree alter their pH when they fall into the water, making it unfavourable for larval development. Another practiced method involves the use of black walnut (*Juglans nigra* L.) and white walnut (*Juglans regia* L.). They bring medical benefits, as they have antibacterial, antifungal, antioxidant, and many other properties (Nael Abu Taha, 2011). Juglone, a toxin in walnut trees, is safe for humans and may prevent cancer growth (Thakur, 2011). However, toxins that may be released from tree roots, bark, and leaves (Kong, Xuan, Khanh, Tran & Trung, 2019) are believed to repel insects. However, this should be studied similar to the Chinese research, which was inspired by folk knowledge and evaluated selected plant species used by the population. Research has found that *Artemisia indica* Willd. shows the most promise among the selected specimens in China (Gou et al., 2020). In Thailand, plants known to repel insects include turmeric (*Curcuma longa* L.), ginger (*Zingiber officinale* Roscoe), pandan (*Pandanus odoratus* L.), cinnamon (*Cinnamomum zeylanicum*), clove (*Syzygium aromaticum* L.), and lemongrass (*Cymbopogon citratus*), (Tisgratog, Sanguanpong, Grieco, Ngoen-Kluan & Chareonviriyaphap, 2016). Research is also being conducted in countries where malaria is a problem. In Europe, smaller plants such as pine (*Pinus* spp.), lavender (*Lavandula* spp.), peppermint (*Mentha × piperita*), garlic (*Allium sativum* L.), rosemary (*Rosmarinus officinalis* L.), and thyme (*Thymus* L.) are also present, whose essential oils have been proven to repel insects. However, precise information on the conditions under which this action would be most successful is still lacking (Singh, Singh & Mohanty, 2012).

Biodiversity and animals

Biodiversity is a path to a resilient city, thanks to the diverse adaptations of animals and plants to climatic conditions (Snep & Clergeau, 2020; Mehan & Mostafavi, 2023). Different plants cope with different weather conditions. Monoculture crops have higher risks, hence the need for fertilizers and pesticides (Winkler et al., 2023). Therefore, a better solution is a flower meadow planted instead of a lawn, reducing the urban heat island effect (Ignatieva, Haase, Dushkova & Haase, 2020; Mody et al., 2020; Winkler et al., 2023).

Like any venture, community gardening requires a high degree of agreement among all participants. Children often compete, but if they are well trained, they will take care of the garden together. This instills a sense of responsibility and competence in the young people and fosters the idea that the growing generations will take care of the GBI in the city, just as they took care of the community garden at school.

The presence of both domesticated and wild animals has a positive impact on children's development. Wild animals appear near schools in search of food or shelter. Farm schools are where animals are raised, and children learn to care for them. An example of such an approach is the Montessori Farm School Folwark Białka, one of the schools within Poland's Warsaw Montessori Family network. This school operates with a work-study program, where children aged 12–18 live, learn, and work by running a farm and, eventually, a hotel. The school has started in the 2022/2023 semester for 10 students but now accommodates 50 students. The director drew inspiration from the exemplary Hershey Montessori Farm School in Ohio. Initially, the director established an urban-based school with farm elements in Warsaw, Poland.

There is an herb garden and an organic greenhouse where students can grow and sell vegetables at a nearby market. They also have a small chicken coop, from which the rooster had to be removed after the first year due to complaints from residents of Warsaw's Mokotów district about early morning crowing. In the new location in Białka, there is a beehive for children to plan, purchase, invest, produce honey, and sell it. This way, they learn about economic independence through making mistakes independently and learning from them. They have lambs, goats, chickens, cats, and dogs. They are also considering having horses, as it is a frequent request from the students. The concept of farm schools appears in many countries but is still not very common.



Fig. 1. St Anthony's Catholic Primary School, Farm and Forest School, Hampshire, UK

Source: ©St Anthony's Catholic Primary School [n.d.].

In the UK, St Anthony's Catholic Primary School, with elements of a farm school (Fig. 1), also gives children opportunities to take care of animals and learn. The farm school is not intended to train farmers but to raise responsible, cooperative, resourceful individuals who understand where their food comes from and recognise that humans are not the most important species on Earth, emphasising the importance of biodiversity and animal welfare.

Aspects of the green-blue infrastructure of schools

The number of new schools in urban areas is increasing, in direct proportion to the influx of new residents. The example of Polish structures shows a steadily increasing share of schools in cities and thus an increasing share of the potential to develop a network of green spaces in the city. Figure 2 shows the change in the share of primary schools (Grades 1–8) in cities and villages in Poland between the 2015/2016 and 2022/2023 school years. In Warsaw alone, there are currently 216 primary schools. In particular, elementary schools, for which the district is still the predominant form of admission according to Polish standards, should have a maximum access radius of up to 500 m², and the recommended area of a plot of land for a school should be 1.5–2.0 ha (Dąbrowska-Milewska, 2010).



Fig. 2. Comparison of the number of children in urban and rural elementary schools. In the 2022/2023 school year, 35.6% of students in rural areas attended elementary schools for children and adolescents, and 64.4% in urban areas

Source: Główny Urząd Statystyczny [GUS], (2023).

From this example, it can be seen that the potential for possible GBI solutions connecting elementary schools is considerable, assuming that the schoolyard areas also include green spaces and outdoor playgrounds and that the surface of the roofs may also indicate additional possibilities for their use.

MATERIAL AND METHODS

The subjects of the analysis are selected examples of green space developments for children's use in school facilities. These are green areas and playgrounds where developments in which aspects of GBI have been used. The purpose of the study was to compare the realisations in Poland against the background of European investments. The selected examples were analysed regarding the feasibility of implementation and the quality of the specific fintech infrastructure solutions. The analysis results also present the participation of individual stakeholders such as owners, designers, people responsible for the maintenance of the place or users – students and their guardians, in the innovation of solutions implemented in the facilities.

RESULTS

Sundby School by Henning Larsen, Nykøbing Falster, Denmark, 2020–2025

The school was designed according to SDGs and involves the local community, as anyone can come and use its facilities (Fig. 3). It is designed with a circular floor plan, and its shape appears to grow out of the ground due to the irregular green roof. In addition to classrooms, the school has a library, a cafeteria, sports facilities, and facilities with music equipment. The school has received Nordic Ecolabel certification, which considers energy consumption and climate. The walls of the school are thatched.



Fig. 3. Sundby School by Henning Larsen, Nykøbing Falster, Denmark

Source: Henning Larsen (2020).

In this case, the roles of the different stakeholders vary. In the case of the above facility, the city can do a favour by financing innovative design solutions that support GBI. This also encourages investors since the city's goal is to become resilient, and GBI plays a key role in this context. A profit-oriented investor can use higher quality materials and engineering solutions with co-financing. Investing in developed infrastructure, especially in public buildings, can also attract publicity and interest by winning environmental competitions and being open to visitors who want to learn about new technologies. Teachers should encourage children to take care of the gardens. The role of parents is to participate in the garden's care and encourage the children. It would be the children's responsibility to use the space safely and to keep it clean and in good shape to support GBI.

Playground Biberland by Gudrun Lang, Hamburg, Germany

The playground in Hamburg's Neugraben-Fischbek neighbourhood is the first water playground in Germany (Fig. 4). It can be used in any weather, including rainy days. The playground consists of cascading channels, watercourses, reservoirs, and equipment. The area collects rainwater from the surrounding streets. The total catchment area is approximately 34 ha, and the playground area is 2,000 m². The collected water slowly seeps into the ground, relieving the pressure on the stormwater drainage system. It is worth mentioning that sanitary and rainwater sewers in many Polish cities sanitary and rainwater sewers are combined in the same installation, so this solution becomes a sustainable alternative. However, there are doubts about the content of the runoff water in which children are supposed to play. There may also be a problem with the amount of water, so the current is not too strong, and the water is not too deep.



Fig. 4. Children's playground Beiberland by Gudrun Lang, Hamburg, Germany

Source: Hamburg.de [n.d.].

Using this example, we can see that cities must plan and find how to deal with occasional excess water naturally in an era of global warming and rapid weather changes. Weather and topographic data collection in the smart city concept greatly supports such studies.

There is a concept of forest schools, one of which is that children are not afraid of weather changes and like to play in the rain. Forest school does not require a large forest, and it is not a regular school. It is a form of hands-on outdoor learning experience in natural environment. It started initially in the USA in 1927 and then developed in Europe in the 2000s: Scandinavia, Scotland, Ireland, and the UK (Emine & Gökhan, 2020). Finally, a training program for forest schools practitioners was developed. Methodologies of forest schools are closely connected to sustainable development. The benefits include confidence, self-esteem, physical motor skills, emotional development, and connection to nature. In addition, outdoor activities promote creativity, teamwork, achievement, manual skills, and understanding of nature (Aydemir & Yiğit Gençten, 2023). Compared to regular schools, children are found to be healthier and have better cognitive functions as they consciously absorb nature with all the senses. Nowadays, in the age of digitalisation, children spend less and less time outdoors (Sella, Bolognesi, Bergamini, Mason & Pazzaglia, 2023). Forest schools sessions should be implemented in every school so that every child can benefit from being in nature. Bringing GBI elements into schoolyards would support this goal. The role of parents and guardians of children should be to organise outdoor play more often, regardless of the weather. Further research on how children can play with water and learn water safety at the same time would be advisable.

A break from the Lawn, University of Cambridge, 2020

King's College's Flower Meadow project (Fig. 5) is an experiment to transform traditional lawns on the 1772 campus into wildflower-filled meadows. By 1984, 97% of wildflower meadows were lost in England and Wales (Griffiths-Lee, Nicholls & Goulson, 2022). The goal of the project was to improve the area's aesthetics and

promote biodiversity and environmental awareness among the college community. The experiment was to stop mowing. There were objections saying that this was tantamount to breaking a 300-year tradition. Nevertheless, an ecological space was created to encourage flora and fauna's growth and promote the harmonious coexistence of humans and nature.



Fig. 5. A flower meadow at the University of Cambridge, UK

Source: ©Geoff Mogridge 2020.

The Flower Meadow has had considerable success within a few years of its inception. Dr Cicely Marshall, a researcher at King's College and the Department of Plant Sciences at Cambridge University, conducted a study to monitor the effects. One of the findings was that of the 33 species sown, 84 are now growing. The wild meadow has become a place of high ecological value, attracting various insects. It has also become popular for nature observation and environmental education, attracting students, employees, and the local community. In addition, the meadow reflects 25% more light than a mowed lawn. This is one way to address the effects of climate change on the urban environment and create green spaces in the city. Wildflower meadows provide multiple benefits to all humans, and pollinators, such as bees, butterflies, and other insects. In addition, living plants absorb pollutants and become an important part of the urban ecosystem (Rózová, Pástorová & Kuczman, 2023).

The Flower Meadow project is an inspiring example of an innovative environmental initiative that benefits both the environment and the academic community. Its success can motivate other educational institutions and local communities to undertake similar conservation efforts. After all, just because we have been mowing lawns for years does not necessarily mean we must keep doing so.

Blue-Green School Project MERITO foundation, Ventura County, California, USA, 2019–2021

The Multicultural Education for Resources Issues Threatening Oceans (MERITO) project was funded primarily by the U.S. Environmental Protection Agency (EPA), the California Coastal Conservancy, and the Channel Islands Harbor Foundation. The goal was to train teachers to teach their students about water science, water

conservation, stormwater runoff prevention, composting, and recycling. Other topics also included watershed, coastal, and island ecology. The project was also aimed to improve students' critical thinking and problem-solving skills through project-based learning. The learning context was the local environment. The project resulted in original proposals to conserve water, reduce waste on school grounds, and protect local watersheds and aquatic ecosystems, primarily to prevent flooding and fires. The plan was to implement the best proposals at five campuses in Ventura County: Sunkist Elementary in Port Hueneme, Montalvo Elementary in Ventura, McKinna Elementary in Oxnard, and Berylwood Elementary in Simi Valley. Parts of the project that focused on flood control included calculating runoff volumes, repairing old and damaged rain gutters (paid for by the school), installing rain barrels, mapping existing vegetation, and designing and constructing a bioswale in an existing native plant garden adjacent to the street.

Early – Years Starter Kit, Rotterdam's Green-Blue Schoolyards program, 2019–2022

The project aimed to introduce more greenery to the school grounds. The premise was to address climate to support children's development in educational outdoor projects. The project was also intended to be helpful as a green enclave for the local community. The program focused on five schools from areas with fewer public green spaces and higher socioeconomic vulnerability, chosen to cover different parts of the city to equalise access to GBI for different residents.

The implementation process was with schools in less green neighbourhoods. They were subsidised with 80,000 euros per school per year between 2019–2022. Activities with social participation elements were required, and participants should be children, parents, and neighbours. The funding would make the areas accessible to residents after school hours.

Opportunities seized: The study found that a strong vision, with the child at the centre of the project, helped build resilience to budget constraints and resistance from school communities. Maintaining and refreshing this vision was essential to ensure the project's sustainability and change the attitudes of education staff, managers, contractors, and parents.

The search for co-funding opportunities and rational management of expenditures made it possible to combine investments related to the Green-Blue Schoolyards program with existing climate adaptation efforts, resulting in larger amounts of money allocated for this purpose.

A data-driven selection process, considering both the environment's quantitative characteristics of the environment and the school's qualitative motivations of the school, enabled the selection of made projects best suited to local needs and increased the involvement of school communities.

Involving schools in project implementation helped anchor the program in the communities and increased local ownership of the maintenance of new green and blue spaces. Technical support from the Speeldernis, drawing on their experience in designing outdoor playgrounds and engaging communities, played an essential role in the program's success. Their activities supported the adaptation of designs to individual school needs and enabled the exchange of experience and support between schools.

Missed opportunities: Implementing the Green-Blue Schoolyards program has encountered difficulties related to complex systems that required the cooperation of many stakeholders with different visions and goals. Negotiating budget constraints, risk aversion, and differing community views on outdoor education and maintenance standards make project implementation difficult. Significant efforts are being made to build and co-create stakeholder visions to address these challenges before implementation. However, with schools at the forefront of projects tailored to their neighbourhoods, piecemeal implementation requires increased coordination to ensure quality control. While other cities manage similar programs centrally, Rotterdam minimises this problem with technical support from the Speeldernis. In addition, inconsistencies between city and national policies on regulations and funding limit the ability of schools to align programs with a child-centred vision. National action is needed to address these inconsistencies.

‘Climate in metropolis schools’ – Tri-City Project Gdańsk-Gdynia-Sopot, Poland, 2021–2024

A project similar to the one in Rotterdam is a joint project of three cities in Poland. As part of the political action for climate education, the Gdańsk-Gdynia-Sopot Metropolitan Area (OMGGS) 2021 launched a project called Climate in the Schools of the Metropolis. This project tries to educate locally and introduce local solutions without a global connection to the GBI. It is funded by a grant from the European Economic Area Fund and the Polish state budget and involves 40 schools from large cities and smaller towns participating. Educational activities will be carried out, and in addition, by the spring of 2024, each school will have implemented a GBI element, such as a green wall, compost pile, rain garden, or retention pond. At the time of writing, the project has completed a phase of teacher training, competitions, exhibitions, and meetings. The project's strengths are in supporting environmental learning in schools and creating examples for other centres.

The key stakeholders are city and school administrators, teachers, parents, and children. The city has provided funding and partners. Their role is to coordinate the project. Their role is to specify the needs of the school. Teachers have received training on climate change mitigation and adaptation. Their role is to share this knowledge and encourage students to participate and benefit from the project actively. The role of parents was to keep up to date with project news to help them participate, for example, in competitions organised by the project. Children should learn and actively participate in the project.

Primary school in Książenice by PALK Architekci, 2011–2012

The primary school in Książenice is located next to an open green space. The area next to the school was designed with the sustainable use of greenery in mind (Fig. 6).



Fig. 6. Storm gardens on school grounds in Książenice

Source: ©Piotr Hardecki 2012.

The designers noted that plants can be a teaching tool instrument in classes on ecological and biological topics. Therefore, the children can grow flower beds in the garden. A rain garden was also designed as part of the GBI. These are retention reservoirs 20–30 cm deep retention basins that fill with water during rainfall and slowly release water into the soil. The evaporating water creates a microclimate that prevents drought

and excessive heat. The development around the school is both a green enclave with a local ecosystem and adjacent to a large open green space that is part of the GBI. If the rain gardens are lower than the surrounding land, they can be preserved for a larger land.

Climate-friendly school – Sendzimir Foundation, development at the King Maciuś I Primary School in Warsaw, Poland, 2022–2023

One of the best Polish examples of an attempt to integrate a school site into an urban GBI system in Warsaw is the Climate Friendly School project, which started in January 2022. The Sendzimir Foundation, in partnership with the Wawer District Office of the City of Warsaw and PS Paaby Prosess Edu Action from Norway, has created an educational centre for the people of Warsaw. As the largest district in Warsaw, Wawer is often flooded during periods of heavy rainfall. For this reason, a project involving a development project at the King Maciuś I Primary School No 195 in Warsaw focuses on rainwater management using green-blue infrastructure. The plan was to create 27 rain gardens throughout the site. The project also includes elements such as a flower meadow, insect and butterfly houses and bird feeders (Fig. 7). Species of designed vegetation have been selected to support native species and the aesthetics of the space. They planned to refresh and replenish the pots in the vegetable garden. The project had a solid educational foundation. Teachers nationwide could benefit from free training and lesson plans with children. The project was informed by a consultation and design workshop with the school's students in April and May 2022. JAZ+ Architekci completed the final project.



Fig. 7. The King Maciuś I Primary School in Warsaw, Poland: A – edible garden; B – flower meadow; C – green roof; D – raingarden

Source: JAZ+ Architekci [n.d.].

The implementation was planned for the fall of 2023 to become a part of the GBI of the Wawer district. A demonstration system of GBI facilities was built up at the school, with an educational path informing about ways to mitigate and adapt to the adverse effects of climate change. The work was participatory: the whole school community was involved (Fig. 7). This project is becoming an example for other schools of how a school site can support the city's GBI while meeting the objectives of the SGDs.

DISCUSSION

Implementation/incorporation of green-blue infrastructure in school areas

The GBI offers many benefits in cities, including environmental, social, and economic advantages. Implementing GBI brings several key benefits to the city, which can be grouped into three main categories: Environmental, Social, and Economic. The environmental benefits meet the key aspects of the Environmental Protection Agency – EPA (2023), which are:

- Stormwater management: GBI helps reduce and treat stormwater at its source, improving water quality and reducing the risk of flooding.
- Air quality improvement: Vegetation in GBI helps remove pollution and improve air quality in urban areas.
- Biodiversity enhancement: GBI supports the preservation of urban biodiversity by providing habitats for various species.

Among the social benefits, there are two main factors, which are health and well-being and aesthetic and recreational values, which are in line with Brear's statements (Brears, 2023):

- Health and well-being: GBI positively impacts human health by encouraging outdoor activities, reducing stress, and improving overall well-being.
- Aesthetic and recreational value: Green and blue spaces create pleasant and attractive environments for recreational activities, promoting a higher quality of life for urban residents.

The critical factor in implementing GBI is the economic benefit factor, which enables the potential to implement new strategies in new and retrofitted areas. The key aspect includes the property value and the creation of new specialised job positions in the market:

- Property values: The presence of GBI, such as green spaces and vegetation, can increase property values and enhance the aesthetic appeal of urban areas.
- Job creation: Implementing GBI can lead to creating jobs in construction, maintenance, and related GI sectors.

The possibility of implementing green roofs, green walls, flower meadows, or natural playgrounds teaches the youngest generation how to take care of the environment. It allows them to benefit from the positive effects of introducing greenery into the human space. Combining GI with BI in school and children's areas improves the microclimate quality and the environment closest to children.

The simplest steps to incorporate GBI into school gardens are a flower meadow, a water pot, and small animal features such as insect hotels. Rain gardens with water harvesting and filtration basins are other steps to introduce better water use. Examples of exposing children to nature include frequent use of shelters and feeders for animals and insects and vegetable gardens.

Studies of Austrian schools show that implementing GBI on school grounds can sometimes be problematic. There are technical issues – complex systems such as green walls require constant weeding and clearing of clogged gutters. In addition, green facades and living walls are expensive. Schools often lack the budget to hire qualified companies to maintain the greenery. The solution can be crowdsourcing, crowdfunding, and networking, using informal connections between schools and stakeholders as the main crowd capital.

A positive development is seen when the funders are municipal services subsidies, local companies or district councils.

Despite extensive knowledge about the positive impact of GI on people and the environment, it is rarely incorporated into public investments such as schools. The main reason for this neglect is the lack of sufficient knowledge about how to finance such projects. The research project MehrGrüneSchulen (Engl.: More Green Schools) launched in Austria to develop financing scenarios. Research shows that children can be involved in the planning, implementation and maintenance of GI elements in the school environment. Children learn responsibility, cooperation, sustainability and other skills. Another challenge is resistance from staff, parents and even students (Teichmann, Korjenic, Sreckovic, Veit & Hartmann, 2023). The concerns of staff and parents are related to the perceived danger of children to nature.

As the King's College example shows, creating a flower meadow is relatively easy. Coghill, the Head Gardener of King's College Cambridge, gives advice on how to start a wildflower meadow (Garget, 2023). In May, stop mowing the lawn and watch what grows on it. To keep the lawn looking neat, it is necessary to mow the edges – these are also important habitats for wildlife. Buying cuttings of ready-made flowers and planting them among the grasses is possible. A more advanced way is to buy wildflower seed mixes. Be sure to choose local species appropriate to the soil and region. It is also worth remembering that wildflowers grow in soils with low nutrient content. Sometimes, this requires removing up to 30 cm of the topsoil from the garden. In King's College the topsoil removal was not necessary (Marshall et al., 2023).

Vegetable gardens are also a good step in planning long-term strategies and appointing a responsible person for educational functions. They are moderately labour and cost-effective and, if maintained systematically, produce the desired results of learning responsibility and gardening skills and a harvest that can be eaten.

While school based GBI offers many benefits for sustainable urban development and educational enrichment, addressing the potential trade-offs and risks associated with safety, maintenance, and governance is crucial to ensure successful implementation. Potential challenges include safety concerns, maintenance challenges, and governance issues. Safety concerns can arise from increased interaction with natural elements such as water bodies and vegetation, which can pose risks to children if not properly designed and supervised. For example, water features must be safe for all ages and abilities, with measures in place to prevent drowning or waterborne diseases. In addition, vegetation in school areas must be chosen to avoid plants that are toxic or may cause allergies.

Maintenance challenges are another consideration, as GBI elements require ongoing maintenance to ensure functionality and aesthetic appeal. This includes regular maintenance of vegetation, water features, and other infrastructure components. Schools must allocate resources for maintenance or partner with local authorities and communities to share the responsibility. Governance issues may also arise, particularly in coordinating the integration of GBI into existing urban systems and ensuring equitable access. There may be conflicts between stakeholders, such as school administrators, urban planners, and residents, over the use and management of these spaces. Clear policies and collaborative frameworks are needed to address these governance challenges and to ensure that the benefits of GBI are maximised for all community members.

CONCLUSIONS

The paper highlights the importance of integrating GBI into school areas as a strategic approach to foster sustainable urban development, enhance biodiversity, and improve the quality of life for city dwellers. It makes a valuable contribution to urban planning by offering insights into the multifunctional use of GBI and its role in creating smarter, more resilient cities. The study provides evidence that implementing GBI in school zones can enhance biodiversity (by providing habitats for various species), health and well-being (by encouraging outdoor activities), aesthetic values (green and blue spaces create attractive environments for recreation),

economic value (by increasing property values), and educational value (by educating children about environmental stewardship and improving the microclimate and environment).

Research on the long-term impact of GBI in school areas is needed to examine the relationship between exposure to GBI in school environments and its influence on educational outcomes, student behaviour, and overall academic performance. It is also recommended that long-term impact assessments be conducted to evaluate the effects of integrating GBI into school campuses on environmental sustainability, student well-being, and community engagement. In cities, there is need to examine how GBI in school campuses can contribute to climate resilience and adaptation is necessary, considering factors such as extreme weather events and heat island effects.

The most necessary action points for future research are to foster collaborative partnerships between academic institutions, local governments, and community stakeholders to co-create research initiatives that address the practical implementation of GBI in school settings. Scientists, designers, and school authorities should advocate for the integration of GBI research findings into local and regional policy frameworks, emphasising the importance of evidence-based decision-making in urban planning and educational development.

Complementary research findings on using GBI in school settings are still lacking. However, it was important to analyse them; this stage was to disseminate the most up-to-date knowledge. It is worth noting that some of the examples analysed have not yet been implemented, so conclusions from the project are lacking.

The GBI is widely believed to provide cities with active and healthier lifestyles, lower stress levels and improved mental health, better stormwater management, reduced heat island effects, and increased property values. However, there is a lack of accurate data on designing GBI to achieve these goals optimally. The GBI system could be supported by, among other things, advanced technologies to monitor and collect data on climate and water levels, enabling faster response and ongoing implementation of solutions. The city would then function as a Green-Blue Smart City. New York is already trying to integrate nature and technology.

Grassroots initiatives that allow for implementing selected elements of the GBI can be seen where institutions have limited budgets, or the legal system does not explicitly allow for implementing planned changes. Participatory activities involving the local community, often the school community, have the greatest impact. The most important part of these projects is building the evidence base – educating teachers, children, and residents. Once established, the most important thing is to continue the work and maintain the garden and retention pond. That is why ecological knowledge is responsible for posing it on to the next generation. In this way, knowledge spreads, and future generations can use this knowledge to go out into the world and develop innovative solutions.

Further projects are needed, under the auspices of governments, in which top-down strategies can be established for all schools as networks of interlinked GBIs within the urban structure, which would constitute centres for climate education – a hub for collecting and analysing information from sensors in the city. Following Western European models, it would be good if the school's green space was also open to the public after school.

Authors' contributions

Conceptualisation: M.J. and A.S.; methodology: A.S. and M.V.; validation: A.S. and M.V.; formal analysis: M.J. and A.S.; investigation: M.J. and A.S.; resources: M.J. and M.V.; data curation: M.V. and Y.M.; writing – original draft preparation: M.J. and A.S.; writing – review and editing: M.V. and Y.M.; supervision: M.V. and Y.M.; project administration: A.S. and M.V.

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WSPIERANIE ZRÓWNOWAŻONEGO ROZWOJU OBSZARÓW MIEJSKICH: INTEGRACJA OBSZARÓW SZKOLNYCH NA RZECZ WSPIERANIA ZIELONO-NIEBIESKIEJ INFRASTRUKTURY MIASTA

STRESZCZENIE

Konsekwencje kryzysu klimatycznego w nieproporcjonalnym stopniu dotyczą ludzi mieszkających gęsto zaludnione obszary miejskie, co stawia deweloperów przed poważnym wyzwaniem w XXI wieku. Administratorzy miejscy stoją przed poważnym wyzwaniem podczas wdrażania celów zrównoważonego rozwoju w praktyce, zwłaszcza w ramach ograniczeń obecnej infrastruktury. W artykule oceniono, w jaki sposób strefy szkolne – które charakteryzują się znaczną liczbą obszarów biologicznie czynnych – są włączane do infrastruktury miejskiej w celu wspierania różnorodnego wykorzystania zasobów naturalnych, poprawiających standardy życia w mieście. W celu scharakteryzowania ewolucji terenów szkolnych oraz kształtowania przyszłych terenów zieleni i zielono-niebieskiej infrastruktury przeprowadzono kompleksową analizę obowiązujących przepisów, przegląd literatury naukowej oraz zaprezentowano studium przypadku wybranych obiektów szkolnych, a także renowacji tego typu obiektów z ostatniej dekady. We wnioskach opisano możliwości, jakie niesie ze sobą ewolucja podwórek i kampusów szkolnych w dążeniu do funkcjonowania zrównoważonego rozwoju oraz wymieniono listę potencjałów miejskich inicjatyw ekologicznych.

Słowa kluczowe: zielono-niebieska infrastruktura, szkoły, inteligentne miasto, zrównoważony rozwój

COMPLEX HEAT EXCHANGE IN BRAKE FRICTION PAIRS

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ABSTRACT

In the article, the following issues are considered: general principles of complex heat transfer in friction pairs of brake devices; radiant heat exchange from the rough surfaces of the metal friction elements of the brakes; the combined action of the fields of thermal conductivity and radiation in the metal friction elements of the brakes. The role of the thermal and dynamic boundary layers resulting from air-washing of metal brakes with open friction pairs and their effect on cooling is discussed. A new relationship between the Biot and Nusselt criteria is shown, which is presented in the form of thermal resistances of the surface and near-surface layers of the brake pulley rim. A comparison of the combined action of the fields of thermal conductivity and radiation in the metal friction elements of the brakes showed that the radiation efficiency is 1.5–1.7 W·m⁻² times higher than the thermal conductivity. Radiation efficiency is the ratio of the power of the heat flux to the unit area through which the heat flux passes.

Keywords: braking device, friction pair, metal friction element, convective, radiation and thermal conductivity

INTRODUCTION

It would not be an exaggeration to say that heat transfer processes are essential and often decisive in almost all areas of thermodynamics and heat transfer; they increase the importance of knowing the laws governing heat transfer processes. At present, the theory of heat transfer represents an extensively well-developed area of knowledge, without which the design and operation of friction pairs of braking devices is impossible.

In all of these cases, when a moving working body interacts with the surface of structural elements of friction pairs of brake devices, there is an intensive heat exchange process called heat transfer (Goodz, Globchak, Koliassa & Yavorskiy, 2007; Sakhin, 2013; DzhanaKhmedov et al., 2016a, 2016b; Kindrachuk, Volchenko, Volchenko, Stebeletskaya & Voznyi, 2017). The main components of heat transfer, and the most complex and laborious in calculations, are radiation, convection and thermal conductivity fields of metal friction elements washed by transverse and longitudinal air flows.

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The operating temperature of brake friction pairs and the ratio of the actual surface temperature of their metal friction elements depends on the degree of equal load on the friction pairs, the friction heat resistance of the linings, and a number of other factors. Therefore, none of the above parameters allows one to objectively judge the energy intensity of the brake friction units. With the same values of operating parameters, one brake mechanism may have sufficient energy consumption, and the other may be insufficient. In view of this, in the study of the processes, phenomena and effects of heating and free and forced cooling of friction units, the experiment, brought in accordance with the requirements of the similarity theory, is of great importance (Balakin & Sergienko, 1999; Nosko, 2010). The results of such an experiment can be used to determine homogeneous quantities in systems in which similar phenomena occur.

According to this theory, research results must be processed using similarity criteria and simplifications, and the dependencies between them should be presented only in the form of criterion equations. Since such an equation is valid only for a group of similar phenomena, it is necessary to know the similarity condition.

In accordance with the third similarity theorem (Dzhanakhmedov et al., 2021), similar phenomena are those in which similar conditions of uniqueness occur. In our case, the conditions of uniqueness are geometric, physical, initial, and boundary conditions. The exact mathematical formulation of the unambiguity conditions is very complex and is fulfilled only for some of the simplest systems of differential equations.

For the brakes of hoisting-and-transport machines, these conditions were formulated by Aleksandrov. He also obtained a criterion equation that connects the temperature complex with similarity criteria, simplexes, which follow from the uniqueness condition. A similar work on the thermal calculation of the brakes of lifting and transport equipment based on the planning of the experiment was carried out by Volchenko (Dzhanakhmedov et al., 2016a, 2016b).

A criterion equation for determining the temperatures of friction surfaces and heat transfer coefficients from metal friction elements of brakes has been proposed by a number of authors (Nosko, 2010; Sakhin, 2013; Dzhanakhmedov et al., 2016a, 2016b).

Considering these equations, it is clear that, along with the positives, they are not devoid of significant drawbacks, the main of which are the following:

- limited scope due to the fact that there is no complete geometric and hydromechanical similarity between the brake mechanisms;
- the difference in the specific power loads of the braking mechanisms is not taken into account;
- some average temperature of the friction surface is determined;
- the setting of boundary conditions of the second kind is carried out on the basis of data on a certain long-term or intermittently operating mode;
- it is impossible to accurately predict the temperature mode of the brakes while the car is moving along the specified real route.

Analysis of the reviewed works revealed the following shortcomings (Kernytskyi et al., 2022):

- the heat exchange processes, despite their different nature, must be represented in pairs “convection – heat conduction”, “heat conduction – radiation”, and “convection – radiation” in the fields of their joint interaction.
- to establish the influence of thermal and dynamic boundary layers, which are washed by air flows, on the cooling efficiency of brake friction pairs when they are open.

The research mainly refers to:

- general principles of complex heat transfer in friction pairs of braking devices;
- radiant heat exchange from the rough surfaces of the metal friction elements of the brakes;

- the combined action of the fields of thermal conductivity and radiation in the metal friction elements of the brakes.

The purpose of the work is to substantiate the features of complex heat transfer in friction pairs of brakes and to establish the reasons for their low efficiency when they are open.

GENERAL PRINCIPLES OF COMPLEX HEAT TRANSFER IN FRICTION PAIRS OF BRAKE DEVICES

In friction pairs of brakes, the main system of heat storage and heat dissipation is their metal friction elements (brake pulleys and drums: solid and self-ventilated discs).

Figures 1a and b show the friction pairs of a disc-pad brake. They consist of friction linings (2), which are located on fixed brake pads. During the frictional interaction of the working surfaces of the linings (2) with the rotating brake disc (1) under the influence of normal pressing force (N), a friction treadmill (3) is formed.

Figure 1c illustrates the friction unit of the band-shoe brake of a drilling drawworks. When the brake band (4) is tightened under the action of normal pressing force (N), the working surface of the friction lining (2) interacts with the friction track of the rim of the pulley (5). The latter is connected to the drum flange using the mounting lug (8).

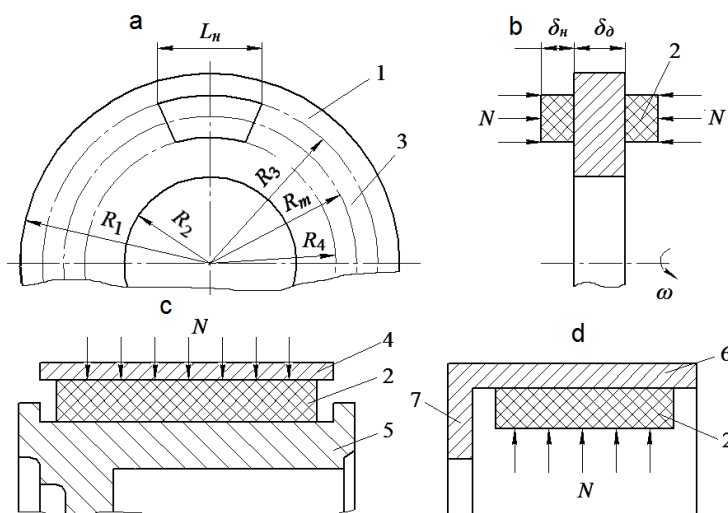


Fig. 1. Diagrams of various types of friction units of brake devices: a – disk-block (longitudinal section); b – disk-block (transverse); c – band-block (cross-section); d – drum-block (cross-section)

Source: own work.

The friction unit of a car's drum-shoe brake is shown in Figure 1d. The unit contains a brake drum rim (6) with a flange (7), as well as friction linings (2) located on the brake pads. When the latter are decompressed in their toe and heel parts, the working surfaces of the linings (2) frictionally interact with the inner (working) surface of the rim of the brake drum (6).

The heat storage capacity of metal friction elements is estimated by the specific heat flux (q) [$\text{W}^{-1} \cdot \text{m}^{-2}$], which penetrates their body and contributes to the creation of a heat conduction field in their cross-section. The polished and matt surfaces of the metal friction elements create radiation and convection fields around

them. However, on their edge, there are thermal and dynamic boundary layers of the washing air with open friction pairs of the brake.

The thermal boundary layer is the layer on the working surfaces of the pulley or drum rim, in which the thermal disturbance of the air washing them is significantly manifested. Thermal boundary layer thickness (δ_T):

$$\frac{\delta}{\delta_T} = \text{Pr}^{0.5}, \quad (1)$$

where:

Pr – Prandtl criterion [-],

δ – dynamic boundary layer thickness [mm].

The thickness of the dynamic boundary layer is determined based on the assessment of the inertia force of the external air flow and the friction force in the boundary thermal layer, from the opposition of which this layer arises (Sakhin, 2013). Dynamic boundary layer thickness (δ):

$$\delta = B \cdot \text{Re}^{-0.5}, \quad (2)$$

where:

B – pulley or drum rim width [mm],

Re – Reynolds criterion [-].

After expression substitution (1) in (2), we get that

$$\delta_T = \frac{B \cdot \text{Re}^{-0.5}}{\text{Pr}^{0.5}}. \quad (3)$$

Let us consider several different “standard” criteria, on the basis of which we obtain one of the main “non-standard” criteria that establish a connection between the thermophysical parameters of friction pairs and high-speed air currents washing them, as well as mixtures in a gaseous and liquid state. Four criteria will be presented below: the Reynolds number, the Prandtl number, the Biot number and the Nusselt number.

The effect of viscosity on the movement of the coolant is characterised by the Reynolds number (Re), which is defined as the ratio of the mass inertia force to the frictional force in the flow.

The inertia force of one-dimensional motion, referred to as the unit volume of the coolant, is equal to $\rho \frac{dv_x}{dt}$, and after formal transformations, we can write that $\rho \frac{\partial v_x}{\partial x} \frac{\partial x}{\partial t} = \rho v_x \frac{\partial v_x}{\partial x}$, where $\frac{\partial v_x}{\partial x}$ is a change in speed when moving from one point in the flow to another. The friction force per unit volume is $\frac{\partial \tau}{\partial y} = \mu \frac{\partial^2 v_x}{\partial y^2}$.

Let us introduce constant characteristic flow parameters, such as density (ρ), viscosity (μ), a certain characteristic velocity (v_c), and a certain characteristic size (B). Then, the order of the sought forces will be

$$\rho v_x \frac{\partial v_x}{\partial x} \sim \rho \frac{v_c^2}{B}, \mu \frac{\partial^2 v_x}{\partial y^2} \sim \mu \frac{v_c^2}{B}.$$

Let us define Re as the ratio of inertial forces to friction forces:

$$\rho \frac{v_c^2}{B} \frac{B^2}{\mu v_c} = \frac{\rho v_c B}{\mu} = \frac{v_c B}{\nu} = \text{Re}. \quad (4)$$

The steady air movement, depending on the ratio of inertial forces and forces (4), can be laminar and turbulent.

The Prandtl number, defined as the ratio of kinematic viscosity to thermal diffusivity, is of great importance in describing the relationship between the velocity and temperature fields (similar to kinematic thermal conductivity) of the coolant, i.e. the ratio of the intensity of the exchange of momentum at the molecular level of a substance to the exchange of heat between the layers of the flow:

$$\text{Pr} = \frac{\nu}{a} = \frac{c_p \mu}{\lambda}. \quad (5)$$

The second important number is the Biot number:

$$\text{Bi} = \alpha_c \frac{b}{\lambda}, \quad (6)$$

where:

α_c – coefficient of heat transfer from the matt and polished surface of the pulley to the high-speed currents of the environment washing them [$\text{W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$],

b – effective depth of penetration of heat into the body of the pulley rim [m],

λ – coefficient of thermal conductivity of the pulley material [$\text{W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$],

a – coefficient of thermal diffusivity of the coolant [$\text{m}^2 \cdot \text{s}^{-1}$],

c_p – isobaric specific heat capacity [$\text{J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$].

The Bi can be considered as the ratio of the parameters of the cooling processes when the mixture of environmental components is washed with high-speed currents to the corresponding parameters of the conductive heating processes of the layers of the brake pulley when the thermal currents reach a given depth of its rim.

The next criterion is the Nusselt number:

$$\text{Nu} = \alpha_c \frac{h_c}{\lambda_c}, \quad (7)$$

where:

α_c – coefficient of heat transfer from the matt and polished surface of the pulley to the high-speed currents of the environment washing them [$\text{W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$],

λ_c – coefficient of thermal conductivity of layers of high-speed currents of the washing medium [$\text{W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$],

h_c – thickness of layers of high-speed currents of the washing medium [m].

In the written expression, the parameters can be considered as relative values of the heat flux density transferred in the heat transfer process from the polished and matt surfaces of the brake pulley when they are washed by high-speed currents of the medium, and the heat flux density through its layers of thickness (h) due to thermal conductivity.

The analysis of the values of the similarity criteria in the conceptual approach from the standpoint of synergy and fractals in tribology made it possible to propose the Volchenko criterion for assessing the state of the cooled working surface of the brake pulley rim and the energy load of its surface and near-surface layers which is determined by the following dependence (Dzhanakhmedov et al. 2021):

$$\frac{\text{Bi}}{\text{Nu}} = \frac{b \lambda_c}{\lambda h_c} = \frac{R_1}{R_2} = V_0. \quad (8)$$

The resulting ratio can be considered as the product of the thermal resistances of the surface and near-surface layers of the brake pulley rim, to which thermal boundary layers, caused by passing dynamic boundary layers of the washing medium, seem to “stick” at the surface temperature of the polymer lining below the permissible level for its materials. At high surface temperatures (higher than permissible for friction lining materials), the binder components of the polymer material burn out. The resulting products are mixed with the circulating layers of air. Then, islands of liquid appear on the surface of the lining, which seem to stick to the working surface of the pulley rim. The control effect on the value of the thermal resistance of the surface layer of the polymer patch is its phase state (solid, liquid, gaseous). For the surface and subsurface layers of the brake pulley rim, the control effect is their energy load. By the value of the Volchenko criterion, it is possible to predict the energy loading of the surface and subsurface layers of metal-polymer friction pairs.

RADIANT HEAT TRANSFER FROM THE ROUGH SURFACES OF THE METAL BRAKE FRICTION ELEMENTS

A number of researchers have obtained solutions for the case when the surface is represented by a model with the following properties:

- i) The root mean square roughness (h) is less than the electromagnetic wavelength (λ) more than 100 μm .
- ii) The surface is perfectly conductive.
- iii) The distribution of roughness heights obeys the Gaussian distribution.

According to Berkhovskiy's method, we consider a plane monochromatic wave with amplitude $A = 1$. At an arbitrary point $P(x, y, z)$ of space, the field of the wave diffracted from the surface is sought (Fig. 2a).

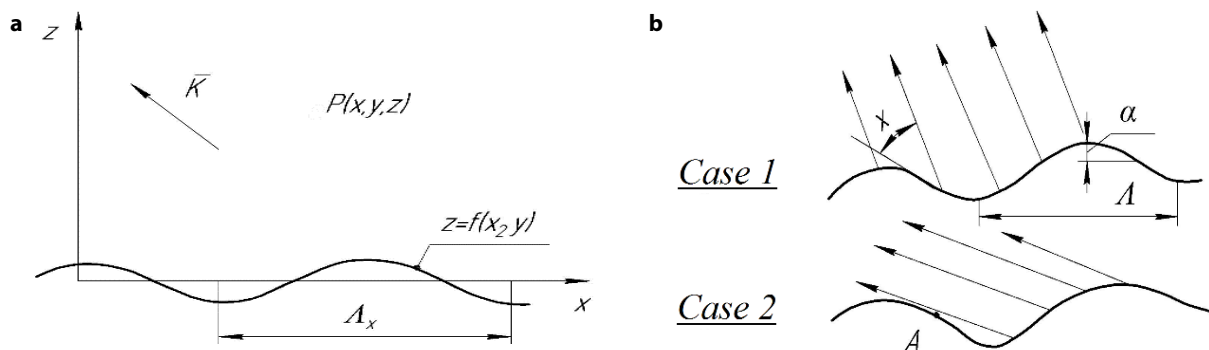


Fig. 2. Considered model of the brake: a – reflection of radiation from the rough surface of a metal friction element; b – Cases 1 and 2

Source: own work.

The coordinate system is chosen so that the X_0Z plane lies in the plane of the rise of the wave. Surface coordinates are denoted by X, Y, Z . This surface is covered with periodic protrusion. Reflecting the surface equation $Z = f(X, Y)$, function Z is periodic. Let us denote by $R = \sqrt{(x - X)^2 + (y - Y)^2 + (z - Z)^2}$ the distance between the desired point P and the current coordinates of the rough surface. As a result of the passage of a wave through a rough surface, an electric potential arises between the microprotrusions of the metal element, as well as the contact spots of the microprotrusions and the levels of the liquid phase of the linings. Then, using the Kirchhoff formula (Belyaev, 1989), one can find the electromagnetic potential at the point P :

$$\psi(P) = \frac{1}{4\pi} \int_F \left\{ \psi \frac{\partial}{\partial n} x \left(\frac{e^{i\chi r}}{R} \right) - \frac{e^{i\chi r}}{R} \cdot \frac{\partial \psi}{\partial n} \right\} dF. \quad (9)$$

Double electrical layers are formed on the polished surface. Double electrical layers are formed on the polished surface. As a result, the electromagnetic potential varied from 0.5 to 1.0 V.

The difficulty lies in defining the boundary conditions. To determine ψ and $\frac{\partial \psi}{\partial n}$ on the surface, the following technique is applied. The reflected wave is considered to be flat. The connection between the waves is set through the reflection coefficient, taking into account the angle of inclination of the surface element at the place of the rise of the wave. A potential, for example, the electric vector of a wave at an arbitrary point on the surface is written as the sum of the potentials of the reflected wave:

$$\psi(x, y, z) = \exp\{l\chi_{\text{ref}} - nz\} [1 + R(\xi)], \quad (10)$$

where:

χ – wave numbers,

l, n – real numbers,

$R(\xi)$ – reflectivity, depending on the angle ξ between the normal n to the surface and the direction of the wave vector (χ_{ref}) of the reflecting wave.

The quantity $\frac{\partial \psi}{\partial n}$ for the reflected wave is determined by the dependence of the form:

$$\left. \frac{\partial \psi}{\partial n} \right|_{\text{ref}} = \chi_{\text{ref}} \psi_{\text{ref}}.$$

The total effect for the derivative (ψ) is determined by the dependence of the form:

$$\frac{\partial \psi}{\partial n} = \left(\frac{\partial \psi}{\partial n} \right)_{\text{ref}} = \chi_o \psi_o [1 - R(\xi)]. \quad (11)$$

In works by Chihos (1982) and Belyaev (1989), examples were considered of using the obtained relations to determine the pattern of radiation reflection from surfaces of various profiles. As a result, relations were obtained to determine the reflection of radiation from surfaces of various metal profiles. As an illustration, we present several diagrams characterising the scattered radiation (Fig. 3).

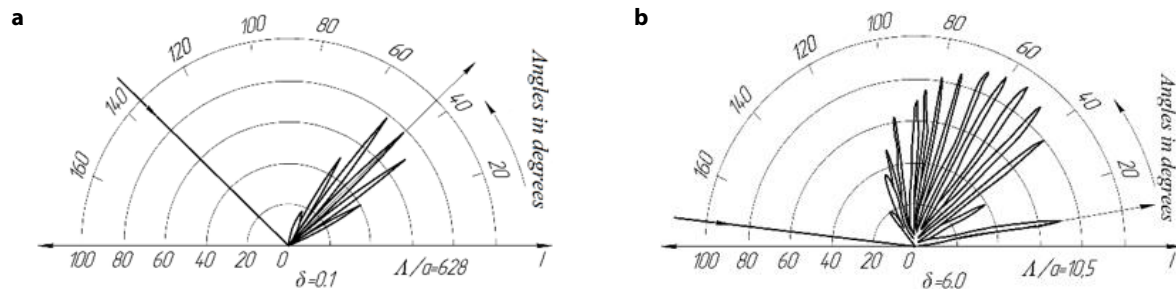


Fig. 3. Scatter diagram of radiation from a rough surface at: a – $\delta = 0.1$, $\frac{\lambda}{\alpha} = 628$; b – $\delta = 6.0$, $\frac{\lambda}{\alpha} = 10.5$

Source: own work.

It can be seen from the diagrams that diffuse scattering $\frac{2\pi}{A} = 0.1$ takes place even with small surface irregularities. In this case, for the values $\frac{2\pi}{A} = 6$ and $\frac{2\pi}{A} = 3$ the maximum of the scattered radiation does not coincide with the direction of the specular reflection, it coincides with the direction of the specular reflection from the inflection points of the sinusoid, where the surface curvature is zero, and the rays experience the smallest discrepancy.

Thus, the Berkhovskikh theory confirms the diffuse nature of scattering even for surfaces that are considered “technically smooth” ($h \approx \lambda$).

COMBINED ACTION OF HEAT CONDUCTION AND RADIATION IN METAL FRICTION ELEMENTS OF BRAKES

Let us consider the combined action of the fields of thermal conductivity and radiation from the non-working surface of the metal friction elements of the brakes. To do this, we will estimate the heat flow for the case of the combined action of radiation and thermal conductivity in the form of the expression:

$$q = \frac{C_0(T_1^4 - T_2^4)}{1 + \frac{3\tau}{4}} - \lambda \frac{T_1 - T_2}{\delta}, \quad (12)$$

where:

C_0 – emissivity, from a metal surface [$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$],

τ – heat flux [-],

T_1 – temperature on the polished surface of the metal element of the brakes [K],

T_2 – temperature on the matt surface of metal brake elements [K].

For simplicity, consider the case when $T_1^4 \gg T_2^4$. Then:

$$-\frac{q}{C_0 T_1^4} = \left[1 + \frac{3\tau}{4}\right]^{-1} + \frac{4}{3} \frac{N}{\tau} \left(1 - \frac{T_2}{T_1}\right). \quad (13)$$

The value of N characterises the ratio between molecular and “photon” thermal conductivity that is the share of thermal energy transfer by true thermal conductivity in comparison with radiation:

$$N = 4 \frac{\lambda}{\lambda_{ph}} = \frac{\lambda}{\frac{4}{3} C_0 T_1^3 l_{ph}}, \quad (14)$$

where:

λ_{ph} – photonic thermal conductivity coefficient [$\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$],

l_{ph} – photon wavelength, i.e., the proportion of thermal energy transfer by true thermal conductivity compared to radiation.

In Figure 4, the comparison of the approximate solution for the combined action, radiation, and thermal conductivity – calculation by Eq. (9) – and the exact one obtained by Viksant and Grosh, as well as Lax by numerical methods from integro-differential transport equations, can be found.

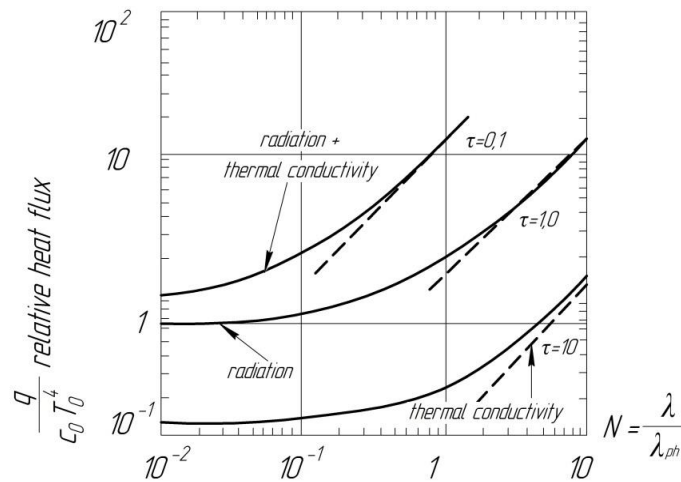


Fig. 4. Determination of the combined effect of thermal conductivity and radiation: the dashes show an approximate solution, and the solid curve shows an exact calculation

Source: own work according to works by Chihos (1982), USSR standard P60-54-97-88 (Gosudarstvennyy Komitet SSSR Po Standartam [Gosstandart SSSR], 1988), Volchenko et al. (2006), DzhanaKhmedov et al. (2016a, 2016b), Volchenko et al. (2019b), Kindrachuk et al. (2019), Volchenko, Volchenko, Polyakov, Fedotov and Evchenko (2019a), Kindrachuk et al. (2021).

Equation (9) was obtained by analytical methods of limiting relations [linearisation of Eq. (9)] near the boundary and taking into account only their thermal radiation far from the working surface of the pulley rim and drum.

Solution for dimensionless heat flux:

$$q_w = \frac{q}{c_0 T_0^4} \quad (15)$$

looks like:

$$q_w = \frac{3(1-\theta)N(T_1) + (1-\theta^4)}{\frac{3\tau}{4} + \psi(T_1) + \psi(T_2)}, \quad (16)$$

where: $\theta = \frac{T_2}{T_1}$; $\psi = f(N)$.

Table 1 shows a comparison of the exact solution for the dimensionless flux (q_w) with the derivation from Eq. (15), as well as a simple summation of the radiation flux, taking into account absorption and the heat conduction flux.

Table 1. Comparison of calculated dimensionless heat fluxes $\tau = 1$; $\theta = 0.5$

N	Exact solution	Acc. the Eq. (15)	Simple summation
0	0.518	0.525	0.536
0.01	0.596	0.573	0.556
0.10	0.798	0.795	0.736
1.00	2.600	2.470	2.536
10.00	20.600	20.300	20.536

From Table 1, for small values of N , the Howell and Goldstein method gives more satisfactory results than the summation of the fluxes. According to Figure 4, the summation of the flows of the combined action of thermal conductivity and radiation of the metal friction element is performed in an approximate and accurate way. Of greatest interest is the fact that using this method, it is possible not only to calculate the flows, but also to construct a temperature profile over the thickness of the pulley rim and drum. In this case, heat transfer, which is “closed” by the radiation field, is considered.

DISCUSSION AND CONCLUSION

Complex heat transfer, in comparison with the combined action of heat conduction, radiation, and free and forced convection due to the presence of concomitant processes, phenomena and transfer effects, is much more complex, which significantly complicates its analytical and experimental studies. Despite these circumstances, it seems possible to assert the following:

- when assessing the efficiency of free and forced air convection of metal friction elements of brakes, it is necessary to take into account the thermal and dynamic air layers. The first is a heat insulator, and the second increases the heat exchange during air exchange. The thermal boundary layer – an area of rapid temperature change – is characterised by a large value of the normal derivative of temperature $\partial t / \partial n$;
- the choice of similarity criteria and their application should occur not only from the modes of movement of the washing of air flows, but also taking into account the thermal resistance to heat transfer;
- when assessing the efficiency of radiant heat transfer from metal friction elements of brakes, it is necessary to take into account their polished and matt surfaces, while the latter are turbolizers of the washed air flows.

Thus, the essence of complex heat transfer in friction pairs of brake devices is disclosed. Thus, based on research:

- the essence of complex heat exchange in friction pairs of brake devices is revealed;
- it has been established that the thickness of the boundary layer of the metal friction element is determined by taking into account the Biot, Nusselt, and Volchenko criteria; using the last criterion, it is possible to predict the energy load of the surface and subsurface layers of friction pairs;
- it has been confirmed that for surfaces considered “technically smooth”, there is a diffuse nature of scattering, that is, the root-mean-square roughness (h) of the surface of a metal element is approximately equal to the wavelength (λ) that passes through this surface;
- it has been established that the magnitude of the relative heat flux is significantly influenced by the increasing value of N , which characterises the relationship between molecular and “photon” thermal conductivity; as the ratio increases, the magnitude of the relative heat flux increases.

Authors’ contributions

Conceptualisation: I.K. and D.V.; methodology: D.V.; investigation: Y.R., D.Z., B.D., I.B., V.R., R.H., Y.S. and D.B.; writing – original draft preparation: I.K. and D.V.; writing – review and editing: O.S. and O.B.; supervision: I.K. and D.V.

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

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ZŁOŻONA WYMIANA CIEPŁA W PARACH CIERNYCH HAMULCÓW

STRESZCZENIE

W artykule rozważane są następujące zagadnienia: ogólne zasady złożonej wymiany ciepła w parach ciernych urządzeń hamulcowych; wymiana ciepła przez promieniowanie z chropowatych powierzchni metalowych elementów ciernych hamulców; połączone działanie pól przewodności cieplnej i promieniowania w metalowych elementach ciernych hamulców. Omówiono rolę termicznych i dynamicznych warstw granicznych wynikających z omywania powietrzem par ciernych z otworami i ich wpływ na chłodzenie. Pokazano nową zależność między kryterium Biota i Nusselta, którą przedstawiono w postaci oporów cieplnych warstw powierzchniowej i przypowierzchniowej obręczy koła tarczowego hamulca. Porównanie połączonego działania pól przewodności cieplnej i promieniowania w metalowych elementach ciernych hamulców wykazało, że efektywność promieniowania jest 1,5–1,7 razy większa niż przewodność cieplna.

Słowa kluczowe: urządzenie hamujące, para cierna, metalowy element cierny, konwekcja, promieniowanie i przewodność cieplna

PRE-DESIGN ANALYSES OF THE MUTUAL RELATIONSHIP AND LOCATION OF MULTI-FAMILY BUILDINGS USING THE EXAMPLE OF THE ARCHITECTURAL AND SPATIAL CONCEPT AT DŁUGOSZA 22A IN WARSAW

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ABSTRACT

When designing multi-family buildings on plots that have not yet been developed, an important element is their location and its careful preparation. Pre-design analyses allow for the simulation of various solutions in order to select the most advantageous location of individual volumes and accompanying spaces. Appropriate arrangement of architecture and other land development functions helps to meet a number of formal and legal requirements, but also provides an opportunity for effective and comfortable living in a future multi-family development. The aim of the study is to show the possibilities offered by pre-design analyses in terms of sunlight and the organisation of space between buildings. Another goal is to outline the benefits of performing such analyses. Thanks to them, it is possible to use compromise in design solutions when it turns out that individual variants of a building location have better or worse properties, or certain conditions are mutually exclusive. The results were presented in the form of variants, presenting various land development solutions and relating directly to the previously conducted analyses. The analyses presented in the article allow for precise formulation of conclusions, and their selection is justified by the possibility of transparent and graphical interpretation of the algorithms performed during design.

Keywords: architecture, multi-family buildings, urban planning, pre-design analyses

INTRODUCTION

The design of a multi-family residential building at Długosza 22a, in the Wola District of Warsaw, is an example of the creative use of various conditions related to location and legal requirements, as well as a unique sense of place (Rybak-Niedziółka, 2018). The concept assumed the construction of a new building on a plot located in the very centre of the urban interior. The interior was marked on three sides by the existing multi-family buildings, and on one side by the kindergarten building with the adjacent recreation and play area. The architectural concept was commissioned by the developer Magmillon sp. z o.o. and designed by architect Andrzej Majewski from MKM Architekci s.c. in 2017. The main problem of the project was not only

to meet legal and technical requirements, but also to create a proposal for the location of the new building in such a way as to meet the needs of neighbours living in local buildings and minimise interference with the area and intangible space (Toparlar, Blocken, Maiheu & van Heijst, 2017). In this study, a number of analyses were carried out and various land development variants were prepared. These analyses fit into the theory relating to the pluralism of the goals of pro-ecological architecture (Kobylarczyk & Marchwiński, 2020). It was important to locate the building as far away as possible from the existing buildings and to adapt to the planning provisions for access roads issued by the city. The designers wanted not only to optimally shade other objects in the neighbourhood, but also to maximise the potential of sunlight. The use of this potential is understood through the use of active and passive solar systems. The shape of the building and the choice of architectural, spatial, material and construction solutions are of great importance for the energy processes taking place between the building and its surroundings. One of the most important issues in this regard is the penetration of solar energy through external partitions into the interior, and in the Polish climate it is recommended to strive for solutions that will make maximum use of heat and sunlight in cold and transitional periods, and provide protection against their excess in hot periods (Marchwiński & Zielonko-Jung, 2013). In addition, a proposal was made to revalorise the adjacent area, which included, among other things, increasing the biologically active area and introducing elements of recreation and integration between neighbours (Davies, Steadman & Oreszczyn, 2008). The presented concept fits into research on pre-design analyses, including location guidelines and those related to legal, administrative and design conditions (van Hoof, Blocken, Timmermans & Hensen, 2016). Moreover, this work raises issues related to urban zoology in the planning of residential areas. They come down to environmental protection by implementing appropriate solutions resulting from analyses of shading of multi-family buildings and their neighbouring surroundings (Kobylarczyk & Marchwiński, 2019). The aim of this study is to show some of the steps involved in pre-design analyses relating to the distance between buildings, shading, and parking solutions. A number of activities are indicated that are important from the point of view of the proper selection of the building's location in the selected area. It is believed that the work presents the characteristics of the analyses and reflects the theories in practice, based on a real example of a conceptual building.

MATERIAL AND METHODS

The study summarises original analyses aimed at identifying the most optimal location of the building in the existing urban space at the conceptual stage. Determining the best location was also intended to meet the needs and expectations of the local population, with whom a number of consultations and arrangements were made regarding the concept for a given plot. The development project was never finally implemented, but serves as the subject of this study. It concerned the construction of an intimate, six-story apartment building with a basement on Długosza street (Fig. 1). The plot is located 2.5 km from the centre of Warsaw. The architectural solutions refer to the traditional buildings in a given district. The building has 18 apartments with an area of 40, 60 and 70 m², and the area of the designed building is approximately 1,000 m² of usable space. On floors I–III, there are two-room and three-room apartments, and on the top floors, there are multi-room, two-level apartments. As part of this study, all the above-mentioned elements regarding a given architectural concept were used and presented in graphic and tabular form. The research material is, therefore, based on the design value, pre-design analyses performed by the author and on the author's own observations with reference to the literature. On this basis, conclusions are drawn.



Fig. 1. Visualisation of an exemplary form of the building late in the evening (concept stage)

Source: Mikołaj Donderewicz, commissioned by Magmillon sp. z o.o., 2017.

The order in which the analyses are performed is specified (After completing all stages, the main design phase should begin):

1. Reconnaissance of the area included in the analysis of existing technical documentation, geodetic maps, orthophotomaps, aerial photos and other graphic materials. Performing an inventory and valorisation of the area. Performing distance measurements in the field using maps.
2. Conceptual and technical analyses, selection of several comparative variants, preliminary assumptions for the designed communication connections, pedestrian and driving routes and parking solutions. Performing analyses related to the solar ecliptic: (a) shading analysis, (b) obscuration analysis, (c) solar insolation analysis.
3. Analyses of distances between existing and planned buildings in the field. Lists of additional factors, consultations and social discussions. Preliminary selection of the best design variant.
4. Analyses of the possibilities of land development and landscape revalorisation.

RESULTS

Reconnaissance of the area

By using the current orthophotomap and map for design purposes, neighbouring buildings were found in the area, which marked the urban interior in a given location. An important aspect of the analytical stage was the characterisation and reconnaissance of a given area (Mirzaei & Haghighat, 2010). For this purpose, a graphic interpretation of the collected conclusions was developed, including measurement data (Fig. 2).

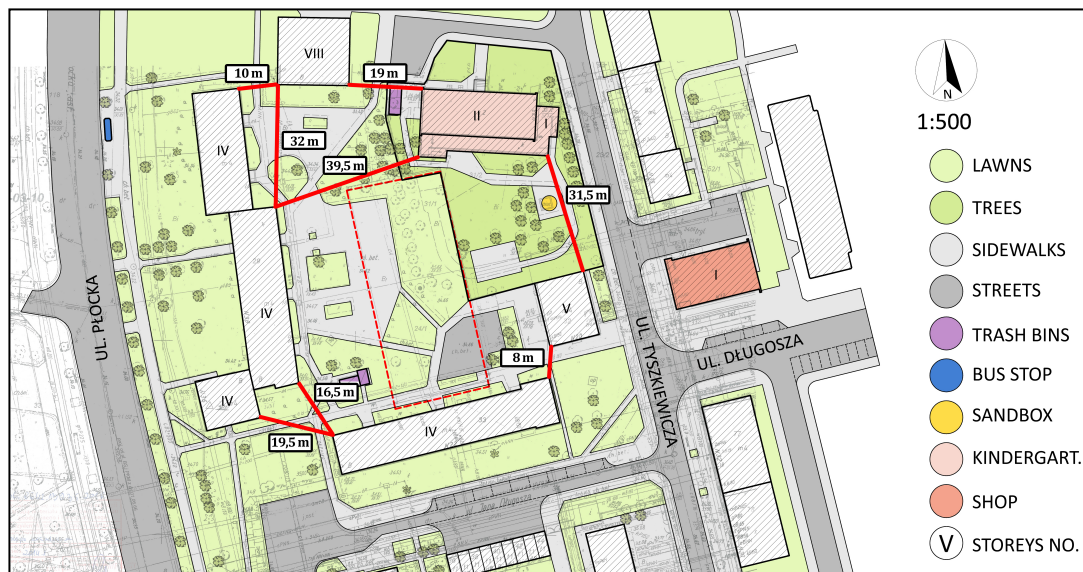


Fig. 2. Inventory and valorisation of the area with building distance analysis

Source: © Mikołaj Donderewicz, 2019.

The distances between the extreme elements of existing buildings were determined and then compared with the distances to the newly designed building in a multi-variant form. Indicating the similarity of given ranges was important from the point of view of the local community (Blocken, 2015). The distances between the buildings were measured, with the smallest distance set at 8 m and the largest at 39.5 m. Performing an inventory of the area is particularly important in identifying local problems. Valorisation of the inventoried area helps estimate the scale of these problems and enables the use of substitute or remedial solutions, which will then translate into a full-fledged proposal for land development.

Conceptual and technical analyses

The distances of buildings to the pedestrian and road transportation systems were measured. The final way of arranging the parking space in the estate and directly on the plot required verification, taking into account the use of appropriate fire protection solutions. It was necessary to check what impact the new access road project would have on the area. It is explained that in some circumstances, e.g. in a given case – in addition to formal, legal, and typically architectural conditions, parking solutions are one of the main factors determining the correct location of the building. This involves the appropriate design of access and fire roads. Depending on whether there is an underground parking lot in the building, the area on the plot will change, which can be allocated to the building development area, access roads or a biologically active area. In addition, the conditions and normatively permitted distances of buildings from parking spaces will change. Underground parking also requires the design of ramps and entrances, for which there is often no space on the plot. It follows from the above that parking solutions are one of the main criteria used when designing the location of buildings and one of the reasons why various parking variants should be analysed. As part of the multi-variant concept, two main, most appropriate variants of the building's location were proposed (Fig. 3).

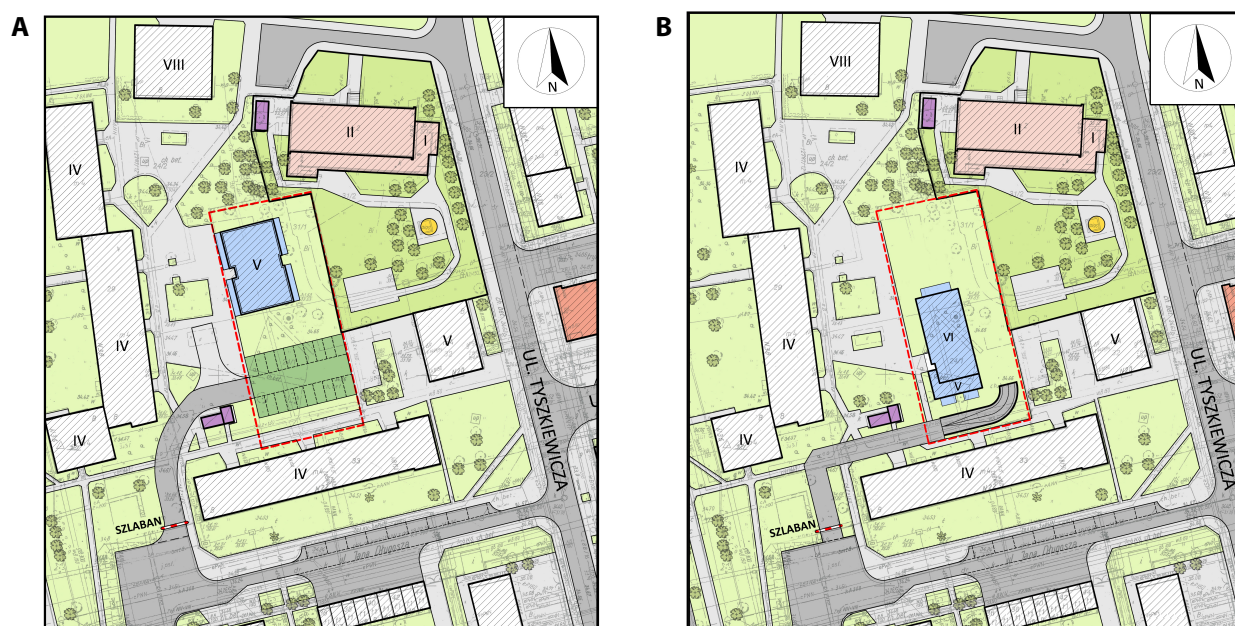


Fig. 3. Variants of the proposed building location, taking into account parking solutions

Source: © Mikołaj Donderewicz, 2019.

The differences related to the method of parking passenger cars and the distance between roads and windows of existing buildings. In the first solution (A), it was an outdoor surface parking lot with a biologically active surface; in the second solution (B), it was an underground parking lot with a direct exit from the road (Fig. 3).

Performing analyses related to the solar ecliptic

Analyses of shading (Fig. 4), obscuration and sunlight (insolation) were carried out, as well as a detailed analysis of the area of impact of the facility on the surroundings – reflecting the requirements contained in the Polish Construction Law (Dz.U. 2023 poz. 682). The research adopted requirements related to the insolation of rooms, where rooms intended for the collective stay of children in kindergartens should have a period of sunlight (insolation time) of at least 3 h on equinox days from 8:00 a.m. to 4:00 p.m., while residential rooms should have a period of sunlight (insolation time) from 7:00 a.m. to 5:00 p.m. In multi-room apartments, sunlight requirements may only be met for one room. In the case of buildings located in the city centre, the required sunlight time can be limited to 1.5 h, and in the case of a one-room apartment in such a development, the required sunlight time is not specified. “Period of sunlight” in law refers to the time during which solar rays are able to penetrate the room and be measured (physically, using tools such as the Sun Ruler, or precise computer software that is based on a 3D model of the terrain and buildings). An additional term for this phenomenon may be the solar insolation time, as required in accordance with the Polish Regulation of the Minister of Infrastructure in the technical specifications that are intended for use and their location (Dz.U. 2022 poz. 1225) and in accordance with the Polish Construction Law (Dz.U. 2023 poz. 682). Precise determination of the scope of shading of buildings in the field was used at a later stage to understand which existing facilities should be examined in terms of requirements related to obscuring and sunlight duration.

As the analysis shows (Fig. 4), the shadow cast by the designed building on the surroundings varies slightly depending on its location on the plot. Between 11 a.m. and 3 p.m., the newly designed building in Variant A partially shades the existing kindergarten, while in Variant B it does not shade it, therefore (B) is more advantageous in this respect.

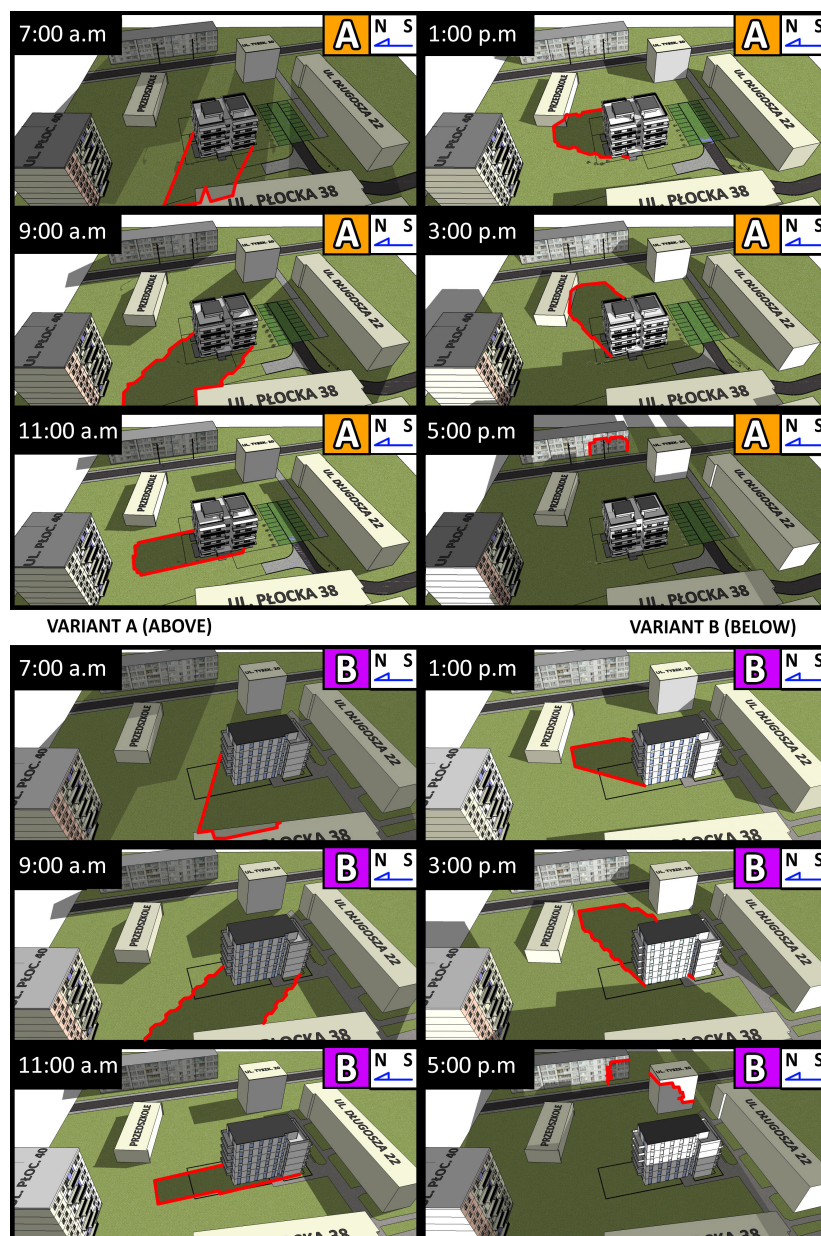


Fig. 4. Graphical interpretation of selected shading analyses results from 7:00 a.m. to 5:00 p.m. on 21 September (one of the two normative test days in the Polish Construction Law)

Source: © Mikołaj Donderewicz, 2019.

Analyses of distances and social consultations

The following variants of the building's location were presented and consulted with local residential communities. It was important to obtain compromise and satisfaction related to the microclimate, problems and conditions of solar management that would satisfy all parties (Moonen, Defraeye, Dorer, Blocken & Carmeliet, 2012). Variant A assumed the amplitude of the distance between buildings between 11–35 m, and Variant B – between 14–50 m (Fig. 5).



Fig. 5. Distance analyses of the designed building to the surroundings, Variants A and B

Source: © Mikołaj Donderewicz, 2019.

The variant of building location that seemed to be the most appropriate for all interested parties due to the above-mentioned factors (Kanda, 2007; Memon & Leung, 2010; Ai & Mak, 2015) was later expanded to include a wide-ranging proposal for the revalorisation of the common area (Grochulska-Salak, 2021). Initially, Variant B was chosen, which was justified, in addition to all the above-mentioned factors, by the fact that it caused the least and normative shading (Fig. 4) of the kindergarten building (building 33).

Analyses of the possibilities of land development and landscape revalorisation

The developer decided to additionally present the recreational and natural potential of the area. An original proposal for land development was prepared (Fig. 6), which took into account the needs of the residents and focused on increasing the planting of trees and shrubs.



Fig. 6. Proposal for land revalorisation and development for the selected Variant B

Source: © Mikołaj Donderewicz, 2019.

In addition, the intensification of the biologically active area was designed, replacing the previously concreted passages and walking paths, as well as a new aesthetic form of waste storage, a common playground, new lighting points, and car passage limiters were introduced as a protective form of greenery. This example indicates that in some circumstances, it is worth considering additional analytical and design processes to increase environmental and social values (Table 1). This makes it possible to obtain a broader architectural context.

Table 1. Summary of proposals and solutions identified for two different design variants

Specification	Variant A	Variant B
Project type	conceptual design	
Standard of solutions	average	
Type of architecture	vernacular	
Basic characteristics of the building	A proposition for a less demanding group of users, economically available to a much wider range of social groups.	A proposal for a more demanding group of users, economically available to a narrower range of social groups.
Receiving social group	large families, student and employee groups, foreigners	small families, managerial or managerial professional groups
Development intention	rental	permanent residence
Residential premises	dependent, flexible	dependent, comfortable
Characteristics of housing premises	The area of rooms intends to meet traditional/basic needs depending on external factors.	
	Susceptible to changes in arrangement and space, use of lightweight walls, multi-room apartments.	Reproducing the livability of single-family houses, presence of apartments, multi-levels, apartments with fewer rooms.
Spatial solutions	The organisation of common space in the context of culture, recreation, sports, learning, integration and relaxation, tailored to specific social groups.	
Parking solutions	parking spaces, and bays	underground garage

Source: own work.

Detailed differences and elements characteristic of both variants are presented in tabular form. The diversity of the proposals oscillated around social, architectural, functional, and spatial and parking categories (Table 1).

DISCUSSION AND CONCLUSIONS

The assumption made at the beginning was to collect various aspects present in the process of creating multi-family residential buildings. A clear bond was the development context, i.e. additional conditions determining the contemporary approach to design solutions. Taking into account the key factors presented in the study, the basic ones that concern the possibility of meeting the needs of residents and the legal norm have been specified (Tofiluk, 2020). The problem of pre-design analyses largely coincides with the understanding of developers and designers, but it could be said that clear goals to be achieved are often set at the beginning, and then it is verified how they will affect specific target groups or further solutions. Then, appropriate decision-making provisions are adapted, and finally, design provisions are adapted (Okeil, 2010). The tendency to search for a set of solutions whose implementation will be most appropriate for particular social groups for financial or location reasons can be specified, and then a full-fledged architectural and construction project can be created on this basis (Starzyk et al., 2023). Distinguishing these factors by location, leading theme, target groups and the type of finishing standard offered leads to naming the criteria on the basis of which the architectural compromise is created (Kanda, 2007; Hong & Lin 2014; Goodfellow, 2019). These criteria, depending on the intentions, will be divided into solid, spatial, material, parking or technological solutions. Depending on the lower or higher standard, other characteristic elements will be present (Turunen, Paanala, Villman, Nevalainen & Haverinen-Shaughnessy, 2010; Chohan et al., 2015). The number of apartments and their livability will require the best possible use of available space for development, and relatively simple construction systems will appear. It will be necessary to arrange parking spaces by designing a larger number of parking bays, ground parking lots or shelters as an alternative to the underground parking floors of the building – which are sometimes problematic in their implementation. Less restrictions will be accompanied by a maximum number

of apartments in the building and savings in the use of residential, common or service areas. The increase in demand for more potential parking spaces forces the organisation of more complex access and garage variants, especially underground ones. The aspects listed in the study may constitute a procedural blueprint and key pre-project issues. The analyses aim to determine the target's desired effect. The aim of such analyses may be to result in multi-variant architectural concepts that can better express the understanding of a given space and the problems associated with it.

Performing pre-design analyses offers:

- a more personalised architectural proposal that better suits the terrain,
- reducing the number of irregularities at later stages of the development, and thus reducing costs and implementation time,
- meet the expectations of the local community,
- the possibility of increasing the volume of buildings to their maximum permissible levels, and thus increasing the number of apartments,
- the possibility to apply greater attention to pro-environmental solutions.

Authors' contributions

Conceptualisation: M.D. and K.R.N.; methodology: M.D.; validation: K.R.N.; formal analysis: M.D. and K.R.N.; investigation: K.R.N.; resources: M.D.; data curation: K.R.N.; writing – original draft preparation: K.R.N.; writing – review and editing: M.D.; visualisation: M.D.; supervision: M.D. and K.R.N.; project administration: M.D.; funding acquisition: M.D. and K.R.N.

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

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ANALIZY PRZEDPROJEKTOWE WZAJEMNEJ RELACJI ORAZ USYTUOWANIA BUDYNKÓW WIELORODZINNYCH NA PRZYKŁADZIE KONCEPCJI ARCHITEKTONICZNO-PRZESTRZENNEJ PRZY ULICY DŁUGOSZA 22A W WARSZAWIE

STRESZCZENIE

W trakcie projektowania budynków wielorodzinnych na działkach jeszcze niezagospodarowanych istotnym elementem jest ich lokalizacja i jej staranne przygotowanie. Analizy przedprojektowe pozwalają na symulację różnych rozwiązań, tak aby wybrać najkorzystniejsze usytuowanie poszczególnych kubatur oraz przestrzeni towarzyszących. Odpowiednie rozmieszczenie architektury oraz pozostałych funkcji zagospodarowania terenu pozwala nie tylko spełnić wiele wymagań formalnoprawnych, ale daje też szansę efektywnego i komfortowego zamieszkiwania w przyszłej zabudowie wielorodzinnej. Celem

opracowania jest pokazanie możliwości, które oferują analizy przedprojektowe w aspekcie nasłonecznienia oraz organizacji przestrzeni pomiędzy budynkami. Kolejnym celem jest nakreślenie benefitów, jakie niesie wykonywanie analiz przedprojektowych. Dzięki nim stosowanie kompromisu w rozwiązaniach projektowych jest możliwe, kiedy okazuje się, że poszczególne warianty usytuowania budynków mają lepsze lub gorsze właściwości bądź pewne uwarunkowania wzajemnie się wykluczają. Wyniki zostały zaprezentowane w postaci wariantów rozwiązań zagospodarowania terenu i odnoszących się bezpośrednio do przeprowadzonych wcześniej analiz. Prezentowane w artykule analizy pozwalają na precyzyjne sformułowanie wniosków, a ich wybór uzasadniony jest możliwością przejrzystej i graficznej interpretacji algorytmów wykonywanych podczas projektowania.

Słowa kluczowe: architektura, budynki wielorodzinne, planowanie urbanistyczne, analizy przedprojektowe

TRANSFORMATIONAL GREEN SUSTAINABLE CONCEPTS IN THE FIELD OF INFRASTRUCTURE

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ABSTRACT

In this comprehensive study, we explore the multifaceted world of green sustainable construction, highlighting innovative techniques and materials. This article presents an insightful exploration of green sustainable construction, focusing on the crucial aspects of architectural design, judicious material selection, and the adoption of optimal structural designs. Through comprehensive literature research supplemented by practical examples, it highlights several innovative construction methodologies that are at the forefront of green sustainable development. These include the use of lightweight framing, cladding systems, autoclaved aerated concrete (AAC), rammed earth, and straw bale construction, each contributing uniquely to environmental sustainability. The study brings to light the looming issue of raw material scarcity due to excessive exploitation, urging for sustainable material management in construction. It stresses the urgency of implementing effective pollution control measures within the construction sector, asserting that such practices are not just beneficial but essential for environmental conservation and sustainable development. This research contributes significantly to the field by providing a foundation for future exploration and advancements in sustainable construction practices.

Keywords: sustainable construction, eco-friendly, pollution, wall materials, housing environment

INTRODUCTION

In this modern era, protecting the environment is a major concern for both developed and developing countries, but due to the unremitting population rate, the demand for housing and its development plan increases day by day. It becomes a challenge for engineers and architects to protect resources and adopt environmental technology in buildings. Generally, the resources existing on the Earth are categorised as renewable and non-renewable materials. Due to the growth of modern technology, the construction industry has become the major exploiter of the Earth's resources – about 3,000 Mt annually – surpassing other sectors described in Figure 1; however, continuously extracting raw materials for construction activities poses future threats. Out of various environmental impact agents, the building sector is considered one of the major phenomena that have a serious effect on the environment (Pacheco-Torgal, 2011; Papanicolaou et al., 2016). The construction industry became not only the largest exploiter of raw materials but also the emerging source of generating pollution –

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it is strongly believed that construction activity damages our environment because of adverse impacts, including loss of biodiversity due to raw material extraction, landfill problems, poor productivity of workers, depletion of resources, acid rain, global warming, poor quality of air, and the production of smog during the manufacture of building products and their transportation.

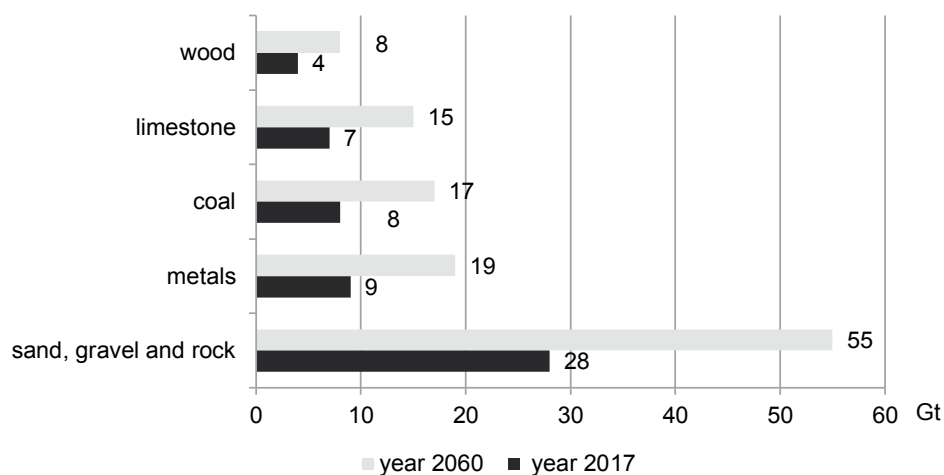


Fig. 1. Estimated consumption of material for construction from the year 2017 to 2060

Source: Organisation for Economic Cooperation and Development [OECD], (2019).

In modern construction, concrete and mortar are extensively used building materials due to their availability and cost; hence, the demand for cement increases day by day, and it directly leads to increasing production. Worldwide every year, it is estimated that cement production alone emits 7% of total carbon dioxide, along with other harmful greenhouse gases (Windapo, 2014). As per a recent study, the current proportion of carbon dioxide in the atmosphere was found to be 550 ppm, with an increment of 2.5 ppm annually and due to this, the mean air temperature has increased at an alarming rate. Additionally, the extraction of river sand through quarrying and mining will seriously impact the environment. In the past four decades, we have faced a lot of negative experiences through the excess extraction of resources, global warming, acid rain, depletion of the ozone, etc. Usually, the impacts during construction are broadly categorised into three types based on the ecosystem, natural resources, and human health. In the case of the ecosystem, fine pollutants are generated in the form of dust during large-scale construction and spread to a large extent. Usually, the dust generated during construction is classified as particulate matter PM_{10} (Song, 2018). Even after implementing several building by-laws and regulations to control those pollutants, health problems for labourers and occupants still exist. In the present method of construction, the materials are more prone to moisture along with the formation of mould, and the presence of toxic substances and particulates in the materials may affect the quality of indoor air, leading to the increase in the possibility of premature death and long-term respiratory ailments such as asthma, chronic pulmonary diseases, silicosis, etc. Additionally, inhaling fragments called respirable crystalline silica – which is commonly found in limestone and aggregates – can cause serious health defects in human beings. Those pollution problems are addressed by creating more environmental awareness and labelling through sustainable and green construction. The term sustainability in the construction field refers to adopting eco-friendly concepts in the case of planning and design to protect the environment at the stage of building construction (Aminu Umar, 2012). Traces of sustainability in our ecological system are found

before the prehistoric period. It has been reported that in ancient times, most Chinese buildings used solar heaters to produce heat energy. In Egypt, for the construction of pyramids, they utilised wind power, and some of the tribes in America still use hot springs as a geothermal energy source in their day-to-day activities. In the year 1970, due to industrialisation, many construction companies began to increase their research and laboratory studies to find eco-friendly materials and practices by using renewable energy in their buildings to achieve sustainability in their constructions instead of using fossil fuels (Muthusamy, Subburaj, Shanmughan, Arunachalam & Raja, 2020). Heavy competition between construction companies leads to developing the methods and materials for sustainability issues.

In practice, the main purpose of using green materials and techniques is to achieve energy conservation and sustainable development, and to improve people's coordination with nature. Achieving sustainability in the field of construction mainly depends on the design and selection of suitable building materials. When selecting sustainable materials, it is more important to focus on their performance specification, the rate of greenhouse gas emission and possibilities to improve recycling and the reuse of materials (Li, Liu, You, Chen & Zeng, 2020). From various literature, it is known that implementing the concept of green sustainability in buildings creates possibilities for the development and productive utilisation of materials, equipment, and practices that preserve the green nature and resources. Through this implementation, it may improve the enactment of building in a positive way for the economy, people, and the environment. From most of the case studies, it was proved that the adoption of green technologies in construction can increase ventilation, control inner room temperatures, improve lighting control, and save energy and resources. As per the latest survey conducted in the USA, it was found that when compared to normal reinforced structures, buildings constructed with the green concept can save 30% of energy on average (Janssen & Hendriks, 2002). The main theme of the study is to describe how green buildings can decrease their environmental impact and degradation and create healthy buildings in the field of infrastructure development for occupants, as well as our natural environment. Since people spend most of their time in residential buildings, the focus was on the technologies and structures that are most often used there.

Green sustainable construction – what, why, and how?

The Greek word 'ecology' means the study of the habitats of various living beings in a scientific approach. In the law of nature, all living beings are related and dependent on one another. As per the principle of ecology, the management of a healthy environment is based on handling its resources effectively and efficiently. The term sustainability refers to the functioning of an ecosystem, society or any community through limited utilisation of resources existing in the ecosystem without harmfully disturbing the environment (Klemm & Wiggins, 2016). The concept of green sustainable development is achieved by developing the skill of living with the support of the environment; hence, the green sustainable concept in the field of infrastructure helps to accomplish a stable environment as well as an economically viable one. When an engineer needs to design a building within the concept of green sustainable construction, it is important to be aware of the goal of sustainability, its background, and its economic possibilities. Due to the growth of industrialisation, the theory of 'ecologically sustainable development' has been seriously embraced by many countries from the year 1970 onwards for the growth of economies and environmental sustainability (Petrovic, Vale & Pedersen Zari, 2017). The construction industry is one of the fastest-growing and longest-lasting fields compared to other industries. In this growing stage, usually, it needs an enormous quantity of raw materials to meet its demand. Construction processes have created many environmental impacts, such as the exhaustion of natural resources, emission of greenhouse gases, ozone depletion, and increases in global temperatures.

As per the U.S. Environmental Protection Agency definition from 2014, green buildings are usually defined as a method of creating structures by way of protecting the environment and its resources efficiently for the entire life cycle of a building by careful consideration of aspects such as design, construction,

maintenance, operation, and repair. In the past few decades, the concept of a ‘green building’ has become popular and spread all over the world with special attention to addressing problems such as global warming, undefined change of monsoons, and controlling emissions from the construction industry (Yildirim et al., 2020). In normal construction methods, it is believed that greenhouse gases are emitted only by using fossil fuel directly as a source to produce electricity. However, in most cases, it was also found that greenhouse gases are also emitted through construction materials during manufacture, transport, construction, operation, and demolition. Generally, the materials utilised in the normal method of construction have several pollutants in the form of harmful chemicals, which may cause serious respiratory complications and headaches to both children and adults (Pacheco-Torgal, 2020). However, in sustainable buildings, naturally, the quality of indoor air is better, and the occupants feel more comfort and satisfaction, which has a good impact on their happiness and health.

In general, a green sustainable building has a positive influence over its lifetime by taking suitable actions for human well-being. These kinds of buildings not only contribute to the health of the environment, but also create many advantages and benefits for the owner and users, such as living comfort, lower capital and operational costs, durability enhancement, less maintenance, and a good indoor atmosphere. It is also important to note that the concept of green sustainable construction is not the same in all countries, because the diverse regions of countries are distinctive based on their culture, climatic condition, tradition, building types, economic status, social condition and environmental priorities, which are considered as the main factors of green sustainable construction (Dipasquale, Rovero & Fratini, 2020). Furthermore, green sustainable construction is defined as a kind of development that needs to meet today’s requirements without affecting future generations. The concept of green sustainable construction possesses different strategies for the design, construction, operation, and maintenance of projects. The design of such buildings and the choice and usage of material which is suitable for this concept play a major role. As per the latest report, if the green sustainable concept was introduced in the urban areas of developing countries like India, it would be possible to save 8,500 MW of power every year. Building green and sustainable buildings is about constructing buildings that augment the local ecosystem using locally available materials (Correia, Santos, Tonoli & Savastano, 2020).

During the design of green sustainable construction, most engineers feel differently and create that in aesthetic, social, economic, and ecological ways. This construction method is believed to be a chance to swap the dominance of human beings over nature and create a fulfilled connection with the world of nature. For the successful implementation of the green sustainable concept, several guidelines are needed to implement it before execution to remove the problems which are obstructing the root of implementation (Zuo & Zhao, 2014). While implementing the concept of green sustainable construction, it is more important to use renewable energy in buildings for both the conservation of energy and the protection of the environment more efficiently than in non-sustainable buildings. During implementation, there is a need to deliberate on the green sustainable technologies, and utilisation of products, systems, and equipment that preserve natural resources and the environment. At the design stage, the cost of a green sustainable building may seem higher, but during the finishing stage of construction, the outcome proved that it was possible to save money in the form of saving energy, less maintenance, and effective utilisation of waste materials (Tiwari, 2001). It was significantly proved that the implementation of green sustainable technologies in construction meets a high level of performance and productivity in the buildings.

The idea of passive design in green sustainable construction

Passive design is an innovative approach to designing buildings with zero energy consumption. The ultimate aim of passive design in buildings is to eliminate the mechanical systems that consume a lot of energy and to provide comfortable facilities for the occupants (Spiegel & Meadows, 2012). Through this design, it is possible to save up to 40% of energy or eliminate the energy needed for heating and cooling. In the passive

design of buildings, the source of heating and cooling is contributed to by natural sources such as solar heat and cold wind. This can be achieved through the proper design of elements such as walls, roofs, floors, and windows of the home, and with this, it also needs to follow the orientation of the buildings (Franzonia, 2011). In a good passive design, the occupants feel thermally comfortable with the minimum energy usage. When designing a passive structure, it is important to consider the following important parameters such as material selection, landscape, orientation, shading, location, massing, insulation, thermal mass, and the position of openings (Fabbri & Morel, 2020). The function of a passive house is described clearly in Figure 2.

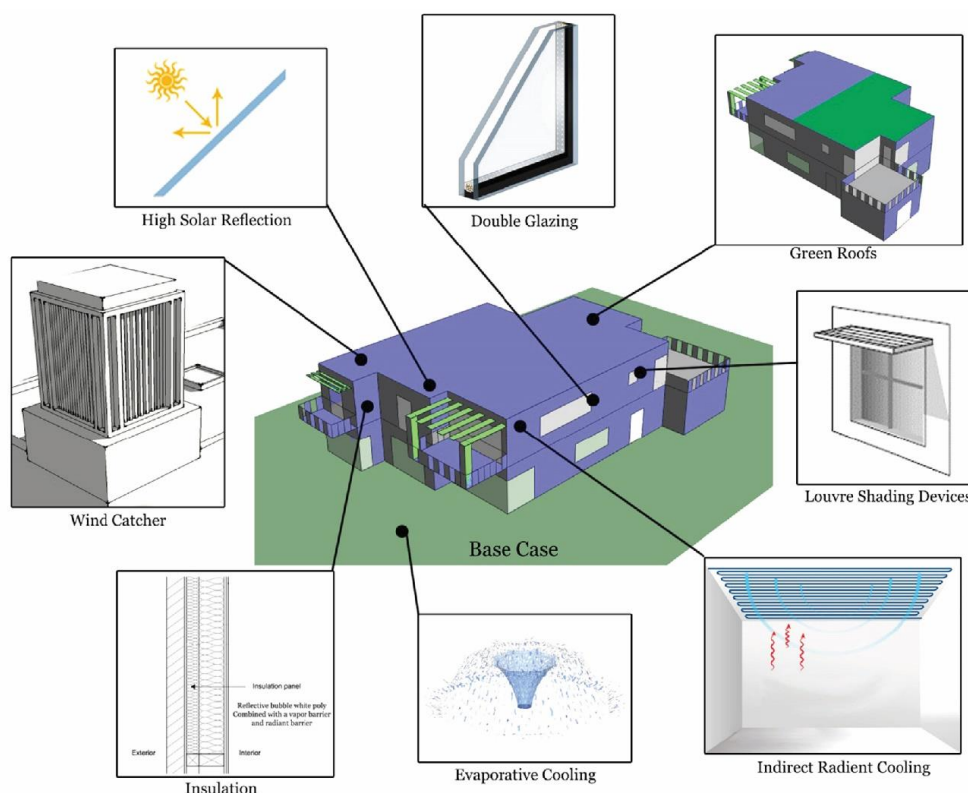


Fig. 2. Passive design model of a building

Source: Taleb (2014).

During the summer season, the sun can generate a huge quantity of radiation in the form of heat directly in each area of the building. At this time, the provision of shading of the outdoor area can reduce the temperature, save daytime energy, and improve the liveability for the occupants. Shading devices such as shutters, eaves, pergolas, window awnings, and planting can block 90% of the heat generated by the sun. To maximise thermal comfort, it is necessary to calculate the different positions of the sun relative to the building's location and analyse the orientation of the building and climatic conditions (Siddique, 2020). The emission of carbon and the generation of high electricity bills can be reduced by up to 25% by providing sealing materials to control air leakage, especially in the winter season. If the gaps are not sealed properly, it can lead to loss of heat and causes problems like condensation and draught. In most passive design constructions, the insulation material acts as a barrier to heat flow, and it also maintains the temperature of a home as cooler in summer and warmer

in winter. The choice of insulation materials is mostly influenced by climatic conditions (Walker, Thomson & Maskell, 2020). Most of the construction materials, such as hollow expanded polystyrene blocks, straw bales, and aerated concrete blocks have low insulating value, and may be used as zero insulation. Generally, insulation materials are broadly classified into two types, such as reflective and bulk. Reflective insulation can resist heat flow radiation due to low emissivity and high reflectivity of heat. In this type, based on the direction of heat flow, the rate of thermal resistance varies (Fenner & Kibert, 2017). In the case of bulk insulation, it can resist the heat which is stuck in the gaps of construction materials and act as a medium for heat conduction. In general, materials such as wool, polyester, cellulose fibre, glass wool, and polystyrene are extensively utilised in bulk insulation.

Before installing any type of insulating component, it is important to address issues such as the development of vapour barriers, air gaps, thermal bridging, and ventilation. Installing insulated components in an existing structure or a newly constructed one can always make significant variations in the energy and comfort demand of a building. Apart from this, it is also essential to discuss an important property called thermal mass in the passive design of the building. It is described as the property of a passive building material to store and absorb heat energy at any given time. If the temperature of high-density materials like bricks, tiles, and concrete needs to change, it requires a large amount of heat energy (Collingea, 2015). However, naturally lightweight materials like timber have low thermal mass. To achieve an effective thermal mass, it is recommended to integrate passive design techniques with the thermal mass of the material. In high-mass buildings, to maintain the ambient interior temperature, it needs to lose or gain a large amount of energy. However, in lightweight construction, the interior temperature of the structure is maintained through its natural properties. In passive buildings, during the daytime in the winter season, the thermal mass of materials absorbs heat directly through the waves or radiation of sunlight, and during nighttime, the absorbed radiation is released from the home (Khandve & Rathi, 2015). In the summer season, the cool breeze at nighttime is stored within the material and is utilised by the hot air during the daytime. Good passive design gives the building more thermal comfort with less usage of energy appliances and reduces the emission of greenhouse gases for the entire life span of the structure.

Main elements of green sustainable construction

The basic needs of all living beings are food, shelter, and clothing. Among all of these, our Earth directly acts as a shelter that protects us from natural calamities and provides constant life support. But now, our Earth is standing at the edge of destruction, and our actions are the primary reason for it. In our everyday lives, the activities and things that we use primarily increase the daily rate of the carbon footprint, which is the prime factor of climate change (Kalpana & Mohith, 2019). This also includes how we construct and maintain our homes. The unmetered usage of resources, energy, and water in our buildings majorly contributes to environmental problems; hence, the concept of green sustainability in the field of construction (Fig. 3) is encouraged to overcome all these issues (Costa, Penna, Magenes & Galasco, 2008).

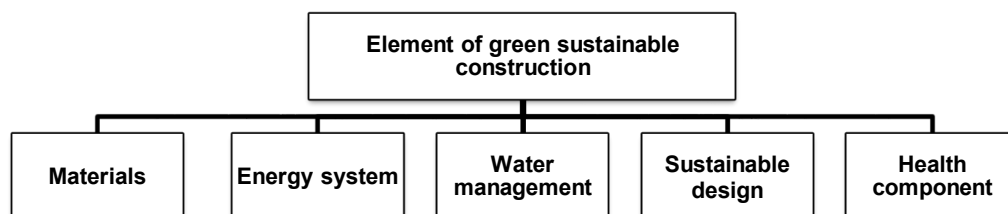


Fig. 3. Primary elements of a green sustainable construction

Source: own work.

Sustainable green construction in the field of infrastructure deals with adopting techniques and strategies to construct a building with the minimum usage of resources and that is environmentally friendly. During design, maintenance, and renovation, a green sustainable building should keep efficiency throughout its lifecycle. The five primary elements, which are shown in Figure 3, make buildings more efficient, effective, and successful (Windstorm & Schmidt, 2013).

Significance of selecting materials for green sustainable construction

Green sustainable construction is a way of utilising resources effectively to meet current demands as well as future demands, and to minimise the serial negative impacts on the environment. In the construction industry, protecting the environment is achieved through using eco-friendly building materials. A concept of green sustainable buildings is that living conditions are improved by giving more attention to the design of buildings and the selection of materials (Magar, 2020). The primary goal of this method is the controlled usage of non-renewable sources of raw materials, and prevention and reduction of waste during construction. In the process of construction, buildings require various materials in their different stages, and the life cycle of the building is determined by the choice of construction materials. In traditional construction methods, materials such as concrete, steel, glass, and aluminium are usually considered high-energy materials; therefore, using these materials in construction may consume enormous energy and increase the level of greenhouse gas emissions. The selection of materials for the construction of green sustainable buildings is considered a very important parameter for its life cycle assessment (Yin, Lawrence & Maskell, 2018). Hence, the process is thought of as a more difficult and challenging one.

The next step involves selecting sustainable building materials by creating an evaluation matrix. Each material used in the project should be evaluated individually to assess its environmental attributes. All the materials are addressed by separate weightage with a rating system to verify whether the material meets the specific goals and objectives of the project or not. Various materials are used in construction today, and each material is required to meet specific complex assembly and functional demands (Taleb, 2014). For example, the materials utilised in the construction of exterior walls generally act as a heat barrier from the temperature of the exterior to the interior, protect habitats from rain and wind, and provide structural stability with adequate exterior and interior finishes. The properties which are desired to meet the demand for green sustainable construction should satisfy the following requirements:

- (i) Materials selected should possess the least amount of volatile/toxic compounds.
- (ii) Use materials that can lower the water requirement of a building.
- (iii) Materials selected should fulfil the quantity needed for a project without compromising durability.
- (iv) Use a lesser quantity of PVC materials.
- (v) During construction, operation, and maintenance, the materials should have the ability to control environmental impacts.
- (vi) Materials selected should have a low maintenance cost, and maintenance should be easy.
- (vii) Materials selected should save energy, resulting in reduced operational costs.
- (viii) Materials selected should have long durability; hence, the necessity of replacing materials in the future is reduced.
- (ix) Materials selected should be able to reduce the amount of waste generated and minimise the unnecessary extraction of resources.
- (x) Materials selected should have low emissions and be able to control pollutants present in the air.

Mostly, the materials are selected during the design stage of the buildings. The evaluation of materials is completed at the manufacture, transport, and construction stages, and at the end of the life cycle of the buildings.

Based on the amount of gas emissions, the environmental performance of materials is examined, and the economic performance is examined by the cost of material and labour. Choosing natural, locally available, and durable materials provides benefits such as using less energy, improving the indoor condition of rooms, controlling air pollution during transport and construction, enabling easy installation, and reducing the overall cost of the project (Magar, 2020). Although several things have been discussed so far, further essential factors for selecting green sustainable materials are shown in Figure 4.

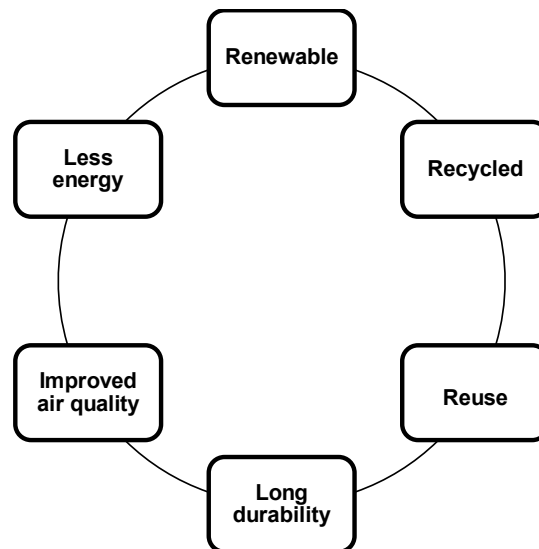


Fig. 4. Factors to consider for the selection of green sustainable materials

Source: own work.

Revolutional concepts in green sustainable construction

As per the previous discussion, it is clearly understood that, during the design of green sustainable buildings, the selection of products and materials should be deliberated as one of the major strategies. The primary objective of utilising green sustainable materials is to achieve better energy efficiency, and using these materials may offer several advantages to the occupants of buildings. In this chapter, it is planned to briefly discuss the properties and application of some modernised green sustainable materials that are revolutionising the field of construction.

Construction using lightweight framing

The method of lightweight framing construction is practised extensively in all developed countries. It consists of a variety of small and uniform components that are closely assembled using steel nailing. Lightweight steel and timber are the major elements that are utilised in this type of construction, and utilising these materials can bring comfortable environmental conditions to the buildings and occupants. Importantly, in areas with highly reactive soils and steep slopes, lightweight frame construction becomes flexible and cost-effective. In this system, the floor element can resist loads from the roof, exterior, and interior walls with the arrangement of suitable footings in the form of piles, piers, posts, or perimeter masonry walls. The appropriate design of openings such as doors, windows, and ventilators can ensure access to natural light, air circulation, and passive solar energy to meet energy demands. In different climatic conditions, a lightweight framing

construction system supports a wide range of innovative glazing, lighting, and shading components to achieve thermal comfort. By using timber, this type of construction has low thermal bridging capacity; hence, it can be recommended mostly in areas like hot tropical countries and very cold regions.

When compared to existing construction materials, the lightweight frame materials perform well under both compression and tension. Through the engineering design of structural steel and timber, we can increase the structural stability of a lightweight frame structure and minimise the usage of materials. In this construction, the floor, which is made from wood, is erected initially and behaves as a working platform for the whole structure. The roof is constructed from the desired floor height using rafters or wooden trusses. The interior surface of the walls is created with gypsum boards in the form of sheathing, which provides smooth finishing, increased stability, and fire resistance, as shown in Figure 5. When selecting timber products, particleboard, fibreboard, and plywood are usually used extensively with jointing, glueing, and laminating techniques to ensure tensile and compressive strength. In the selection of steel components, hot-rolled or thin steel sections are mostly used to gain maximum structural stability from the minimum thickness of steel (Lawson, 1996). In general, this form of construction is considered to have low thermal mass and is unable to store passive heat. Due to their low thermal mass, these types of buildings will respond efficiently and rapidly to auxiliary cooling and heating. The insulation level of these structures entirely depends on the depth of the components adopted. It is known that steel is a good conductor of heat and efficient in thermal bridging, and timber is a natural insulator material, but it is inefficient in thermal bridging. Therefore, to maintain the temperature, an artificial insulation layer made from foam-based materials is applied externally, behaving as a barrier against the vapour, preventing condensation, and maintaining the interior temperature (Radhi & Sharples, 2014).



Fig. 5. Typical cross-sectional view of a wall in a lightweight frame construction: 1 – gypsum plasterboard; 2 – cold-formed steel profile; 3 – mineral wool; 4 – oriented strand board (OSB); 5 – external thermal insulation composite systems (ETICS) with thermoplastic expanded polystyrene (EPS)

Source: Santos, Simões da Silva and Ungureanu (2017).

In the case of sound insulation, the materials used in this construction are not efficient as sound travels along the surface of walls, floors, and roofs. Therefore, materials with a minimum level of sound insulation properties are chosen to minimise the transmission of sound. The openings provided for doors, windows, and ventilation are the major sources of sound transmission; hence, it is necessary to close the gaps between the openings with suitable sealants (Radhi & Sharples, 2014). Soundproofing sheets are available commercially as floor and wall elements to control the high emission of sound. During fires, timber rapidly loses its strength; therefore, to achieve better structural integrity while exposed to heat, plasterboard with high fireproof capability is used in this construction at different specifications and thicknesses. Light framing using steel and timber offers stylish design at a reasonable cost, and due to the advancement of technology, there are possibilities to extend the design with minimum resource consumption.

Construction using cladding systems

The exterior appearance of a building is a key element in deciding the quality of a building. Sometimes, due to adverse climatic conditions, the exterior wall surfaces are subject to large defects, and it directly affects the structural integrity and aesthetic appearance of the building. The exterior walls act as a barrier between the inner and outer environments, and the energy consumption of the building also depends on the thermal conductivity of the exterior walls. Therefore, to maintain efficient thermal conductivity, cladding is used. Cladding is like a non-load-bearing component attached to the exterior surface of the walls to protect the buildings from most rainwater and heat. This type of component usually has long durability and improves the aesthetic condition of buildings, as well as provides fire resistance, a smooth, non-dusty surface, and heat and sound insulation, mostly in polluted environments. For every type of project, varieties of cladding are available, and they are quite difficult to explain from one another. Materials such as bronze, stainless steel, copper, and rubber are utilised in the manufacturing of cladding. The system for installing cladding is different, and it's decided based on the type of material used. Sometimes, the claddings are prepared as a composite with a combination of materials such as wood, vinyl, plastic, metal, and masonry. To allow water vapour from the inside to the outside of a building and to maintain the humidity in the room interior, claddings are fixed or placed directly to the walls or in the frames.

Technically speaking, cladding systems are broadly classified into two types: cladding layers and wall systems. In the cladding layer system, the proposed claddings are fixed on the outer finished layer to cover structural components and the outer walls. Through this, the environmental performance, appearance, and thermal condition of the building are enhanced and outdoor pollutants are also kept away. Due to the advancement of construction materials and building technologies, different cladding systems are available on the market. In-wall systems are classified into two types: barrier walls and cavity walls. At the time of constructing exterior walls, the barrier wall system is preferred; through this system, it is possible to integrate the construction joints with the outermost surfaces of the exterior walls. While using this system, the thermal mass effect becomes long-lasting, and the materials used in this method can be recycled and reused in the future. Cavity wall systems are preferred for pressure equalisation in altered climatic conditions. While comparing both systems, we can find a lot of diversifications in their type, thermal performance, fire safety, protection from moisture, durability of the material, acoustic performance, and maintenance. Because of the effect of this system on the environment, its energy performance is varied. Mostly, the structural components of mass wall systems are associated with masonry and plaster cladding systems. In the barrier wall system, polished solid metal plates with exterior insulation, precast spandrel panels, and composite cladding systems are widely used. For the proper functional requirement of a building, it is necessary to select a particular cladding. The poor design of cladding may affect the environmental and thermal condition of a building. The cladding system consists of vertical or horizontal boards, overlapping panels, or sheet materials in the form of tiles and shingles (Fig. 6). The effectiveness of those cladding systems varies based on the intensity of rainfall, the speed of the wind,

and its direction. The exterior cladding should have the ability to absorb heat and reflect it, which is also based on the colour of the cladding. Therefore, choosing the colour is of utmost importance, and it's suggested to use a light colour with reflective finishes in hot climates, and for colder climates, dark-coloured cladding systems can be used, especially for roofing.

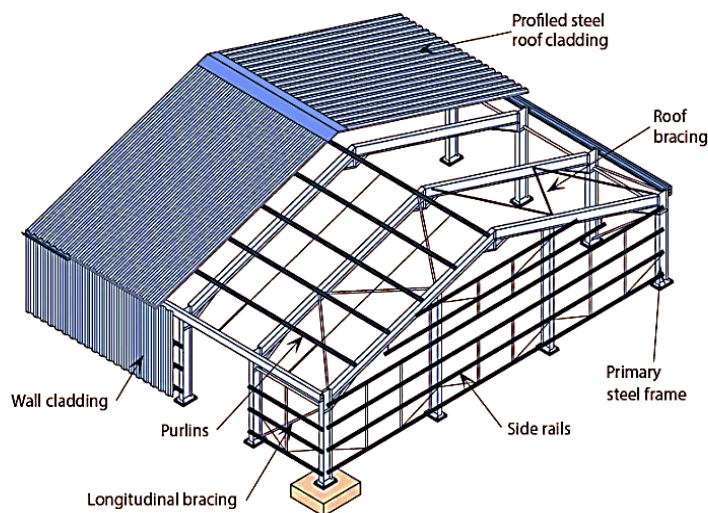


Fig. 6. Industrial building with wall and roof claddings

Source: SteelConstruction.info (2023).

The cladding systems are designed with variations in angles, both horizontal and vertical orientations, and shadow patterns. In a well-designed cladding material, it is noticed that a better appearance and perfect appearance occur in specific conditions. The risk of condensation during heat insulation can be eliminated through adequate design and fixing of vapour cavities in suitable places. The thermal performance of a lightweight framing system can increase using high-mass claddings. Apart from conventional materials, nowadays, claddings are also prepared with agro-based materials like paddy straw and waste paper in combination with bitumen. These products serve as good sound insulators and can be a thermal reflectance. The use of a cladding system can offer possible methods to reduce the environmental impact of the buildings by selecting the proper materials and systems.

Construction using autoclaved aerated concrete

Autoclaved aerated concrete (AAC) is a type of concrete that is made by combining expansion agents with cement and aggregate. It was developed in Sweden by an architect in 1924. At hardening, this type of concrete consists of nearly 80% closed air pockets in its total volume. Due to the presence of air pockets, this concrete is considered lightweight and highly energy efficient. This type of concrete is generally factory-made by placing concrete in a mould with a foaming agent and then cutting it into panels or wire-cut blocks to form the desired dimensions. The molecules in this type of concrete perform well in sound and thermal insulation. When compared to conventional cement blocks, the blocks prepared using autoclaved aerated concrete are lightweight, resist large structural loads, and are an excellent barrier against fire (Raj, Borsaikia & Dixit, 2020). During masonry work, these types of blocks are cut and shaped relatively easily using simple hand

tools to the needed dimensions. Autoclaved aerated concrete-based components are extensively used for roofs, walls, and floors. The AAC blocks have equal dimensions; therefore, when used for wall construction, they require less mortar and provide a uniform finished surface. Generally, AAC is light in colour with the presence of visible perforated void particles. Hydrogen gas is used as a foaming agent to react with alkaline materials present in the cement to create small holes within the concrete. Through these holes, the insulation properties of the material are enhanced. To improve the durability of AAC products, some materials, such as natural stone and polymer-modified stucco, are added to the main ingredients (Ferretti, Michelini & Rosati, 2015). However, through these holes or air pockets, water may percolate; therefore, suitable damp-resistant solutions are needed over the surface to prevent the penetration of water.

AAC products are available in the form of blocks, and floor and roofing panels with reinforced lintels. Walls using AAC blocks are constructed using a thin bed of mortar similar to conventional brick masonry walls, and the panel components are erected vertically up to the full height of buildings. The wall panels used for the exterior are generally made as precast units and act as a load-bearing component for buildings with a maximum of two floors. In AAC panels and lintels, structural adequacy is ensured by integrating the steel reinforcement during design and installation, whereas the AAC floor panels are considered as non-load bearing members and heavier (Narayanan & Ramamurthy, 2000). During the erection of floor panels, special care should be taken, and skilled carpenters need to be employed. The thermal performance of AAC blocks is based on the type of climate in which it is used. Due to a combination of air pockets and concrete, the AAC blocks naturally have thermal mass performance, and it is fully achieved when used in flooring and interior works. Compared to the compressive strength of conventional concrete products, the AAC specimens have enough strength and also possess a one-fifth density value of normal concrete, and it is recommended that the AAC blocks are suitable for load-bearing structures. An eco-friendly building is constructed with AAC blocks, as shown in Figure 7.



Fig. 7. Eco-friendly building constructed with autoclaved aerated concrete (AAC) blocks

Source: Daphne Construction (2023).

In the case of thermal insulation, the AAC products meet the same requirements as other masonry; however, it is necessary to provide additional insulation in the form of plasterboard lining to enhance the insulation capacity further. The closed air pockets present in the AAC products act as acoustic materials, and they improve sound insulation effectively (Raj, 2020). For better improvement of sound insulation in AAC constructions, it is suggested to incorporate the asymmetric cavity system within the walls. The materials utilised in the AAC products are mostly non-combustible and inorganic; hence, damage due to fire occurs at a very low rate. Due to its porous nature, the AAC elements are more prone to moisture penetration, especially in harsh climatic conditions; this can be avoided by appropriate design. In terms of sustainable perception, AAC products offer both performance and material aspects. Because of its huge air gaps, AAC products use fewer raw materials than any other construction materials. During testing, it was understood that using AAC material in construction can save 10–20% of the energy required for the heating and cooling system of buildings (Narayanan & Ramamurthy, 2000). The AAC products are usually aerated; therefore, the air circulation within the buildings is greatly improved, and the material does not contain any harmful toxic substances. Hence, there is no chance of any breathing problems for the occupants. However, while manufacturing, the crystalline silica compounds present in the materials may cause some damage to the lungs while inhaling. It can be prevented by using suitable safety protection such as gloves, respiratory masks, and eyeglasses. Additionally, as a single material, AAC has major advantages in both construction and environmental issues, and the investment of material and energy utilised in these products proves that the buildings are intended to stand for a long period of time.

Construction using rammed earth

In many older civilisations, certain types of soils are used as building materials. In traditional practice, materials such as sand, gravel, clay, and silt are compacted at high pressure until the materials attain homogeneity, and often, they need to be compacted repeatedly with the help of wooden poles. To increase the durability and strength, cementitious materials may be added to the compacted soil at a rate of 5–10%. Under different environmental circumstances, the life period of rammed earth material increased through the provision of air sealants with added protection. Around the world, many rammed earth constructions have remained in good condition for many centuries. For example, the Hakka roundhouse shown in Figure 8 was constructed in China 1,000 years ago (Kebao & Kagi, 2012). In rammed earth construction, most of the energy is utilised for quarrying and transporting the raw materials to the site. However, in modern times, stabilising the rammed earth requires difficult labour work, powerful arms, and large mechanical support. Most of the rammed earth materials have less insulation but have good thermal mass. The stable compacted earth material can be used directly in the form of blocks or placed layer by layer in between formworks. Based on the mineral constituent of earth material, the colour of rammed earth material is different. To improve or show the variance in colours, the aggregates should be dipped in different coloured pigments and incorporated into the construction. To get different shapes in this type of construction, the frameworks should be selected with unequal finishes that can be utilised and removed after the wall has been constructed (Easton & Easton, 2012). Generally, the construction materials derived from rammed earth are considered stronger under compression; hence, they are recommended as load-bearing components in the construction of multistorey buildings.

Like reinforced concrete, rammed earth materials can achieve high strength within a short duration. If the reinforcement provided in any form can cause serious issues, it is not recommended. This method of construction is based on onsite activities, so it is important to select the perfect earth material and formwork to minimise the difficulties arising in the construction by planning the services well in advance. When selecting the raw materials, it is important to follow the method of control during batching and sourcing of materials. The thermal mass of rammed earth materials is quite high, and sometimes, the thermal mass of materials is reduced by the passage of heat that travels through the walls (Lindsay, 2020). To limit the energy consumption

in these types of walls, they should be properly insulated based on the requirement of cooling or heating. In alternative climatic conditions or variations of daily temperature, the rate of heat flow is reduced by the thermal mass of rammed earth material within the building envelope for nearly 10–12 hours. In heavy cold seasons, the rammed earth walls become a battery of thermal storage, and they provide sufficient heat for occupants whenever needed. In most tropical countries, rammed earth construction is not recommended due to exhaustion from overheating, and the occupants can feel more thermal discomfort. If the insulation properties of rammed earth walls need to increase, the wall thickness also needs to increase, and the insulation is introduced by the provision of a lining within the rammed earth wall. Increasing the thickness of walls during insulation may change the structural behaviour of the walls and increase the project costs (Dipasquale et al., 2020). Meanwhile, the provision of insulation in rammed earth buildings can offer advantages such as texture, acoustics, feel, aesthetics, and low maintenance. The insulation materials must attach to the exterior portion of the wall, and only then does the insulation meet the construction requirements.



Fig. 8. Hakka roundhouses using rammed earth construction, China

Source: Wallis (2012).

The noise transmission and reduction are based on the density and thickness of the wall. Rammed earth interior walls have a high ability to control the sound insulation between different rooms due to their monolithic nature. The materials that are used in the earth walls have good sound reverberation properties and do not generate unwanted echoes like conventional walls. No flammable materials are present in the earth materials; hence, the fire resistance property is good. High durability is the main advantage of these types of construction, but most earth walls are subject to long-term moisture damage due to the porosity of earth particles (Tiwari, 2001). During prolonged moisture exposure, the internal surface of the material may become degraded. Therefore, it is advisable to protect the bottom and top portions of the walls with the proper sealants. On the market, waterproof additive materials are available, and these kinds of materials keep the rammed earth in a breathable condition for a long period. The walls constructed with rammed earth need extremely low maintenance. Once the construction is over, no further attention is needed, at least for 10–20 years. Due to the natural aesthetic appearance of exterior walls, there is no need to spend money and time on painting. Walls constructed with 300-millimetre thickness are load-bearing, and no further structural components are

needed. The rammed earth utilises a low energy impact, and the onsite material is enough to meet the demand for construction and reduce the impact of pollution on the environment.

Construction using straw bale

Utilising straw bale for construction is an innovative and sustainable method that uses blocks of straw derived from rice, oats, wheat, or rye and can be used in the form of building insulation and as a structural element. Bales are usually available in the form of two strings and three strings with a typical size of 90 cm long, 45 cm wide, and 35–40 cm high and weigh about 15–20 kg. In green sustainable construction, a building constructed using straw bales is considered a natural building and is otherwise known as brown construction. Straw bales were used over many centuries in the form of thatched roofs and also used with the earth walls in the form of wattle and daub. Straw is a byproduct of grass, which consumes the sun's energy while growing, until it is harvested (Jenkins Swan, Rtiel & Lovegrove, 2011). Straw bales were first used for construction by the people of Nebraska, USA, over a century ago. The major compounds present in the straw are cellulose, silica, hemicellulose, and lignin; therefore, the straw can easily be mixed with soil and form a material called mulch. Walls constructed using straw bales usually have a smooth finish, and earth and cement materials are applied over the finished surface as a rendering to cover the straw bales. The appearance of the finished wall surface is more textural and aesthetic. A load-bearing wall constructed using straw bales is shown in Figure 9.



Fig. 9. Load-bearing wall constructed using straw bales

Source: Walker (2016).

In straw bale construction, the stacked materials are kept in the form of rows over a raised foundation. With this, the straw bales and the supporting platform are constructed like a set of lateral arrangements and the moisture barrier is inserted in between. For longitudinal support, stacks made up of timber or bamboo are provided in the form of pins to hold the bale walls in position, and sometimes, along with these stacks, mild steel mesh also provides lateral support to increase structural efficiency. Later, the finished wall surfaces are

plastered using lime or earth-based materials, and the selection of plastering materials is decided based on climatic conditions (Li & Yeung, 2014). Generally, walls constructed using straw bales act as load-bearing for a building. However, they can also protect buildings from seismic and wind loads. Based on research, it was found that straw bale construction has remarkable qualities, and it also suggested that it can be used to construct up to three storeys. Straw bales are usually composed of mostly air; hence, they have low thermal mass. However, plastering materials such as earth and cement have moderate thermal mass, and there is a chance to apply that thermal mass on the exterior and interior portions of the insulated straw core. It is recommended to maintain the 75-millimetre thickness of the plastering material to provide significant thermal mass. In the case of insulation, straw bales have perfect insulation properties compared to other green materials (Correia et al., 2020). When designing any type of building, a special requirement is to arrange and integrate the insulation performance with the overall performance of the building. Likewise, in the design of straw bale buildings, it is also important to provide insulation in the windows and roofs to maintain their overall performance. When compared to conventional buildings, straw bales provide better resistance against sound. Because it is lightweight, the materials provide significant quietness and contribute to the liveability.

In case of a fire, a tightly packed dense wall constructed with straw bales is an airless environment; hence, the chance of a fire is impossible. However, any loose opening may increase the possibility of fire affecting the inner core of the bale construction. To prevent this, suitable air-sealing materials should be introduced during construction. Strict monitoring is needed to ensure the absence of sawdust and loose straw materials during construction. The straw bale walls have excellent resistance against termites; however, traps and bait near the finished surface can prevent the infestation of termites and mice in the future. During prolonged exposure to water, the cellulose present in the straw bales tends to grow fungus that leads to the development of rot, and is considered a major drawback in straw bale construction. It can be prevented by constructing the straw bale wall in a more waterproof way (Berndtsson, Bengtsson & Jinno, 2009). In terms of air pollution, the straw bales can store carbon in vast quantities and thus control the level of pollutants present in the air. The emission of greenhouse gases in straw bale construction is 50% less than in any other concrete construction. The rate of renewable compounds is higher in straw bales, and for long-term applications, the straw bales must have good soil conditions with ecological integrity. Using straw in construction has vast advantages for the environment, and it enables buildings to use less energy and cost less throughout the building's life.

Life cycle assessment of green sustainable materials in construction

Selecting materials in green sustainable construction plays a major role in the evaluation of the environmental impact of a building during its entire life cycle at various stages. Life cycle assessment (LCA) is the tool used to evaluate the impact of the environment in an effective way. The method of life cycle assessment of green sustainable building material is clearly stated in Figure 10 for future investigation. Since 1990, LCA has been used as an important tool for assessing the impact of buildings. In the field of green sustainable construction, LCA has helped building code officials and consumers make clear decisions during the design and construction stages. Also, it explores opportunities for manufacturers to find innovative products with quality and efficiency. A number of tools are available to assess the building environment, energy labelling, selection of construction materials, and indoor air quality. LCA was initially used in the USA and Europe for product comparison, but today, it is widely applied in product design, strategic planning, and government policy (Bribián, 2011). Through LCA, it is possible to assess the environmental impact of buildings on other structures, and additionally, it provides a way to reduce environmental impact through the implementation of trade-off analysis. Generally, the concept of LCA has complex structures that focus on energy and pollutants, and the flow of material both internally and externally within the life cycle perspective. The complexity in LCA means making enhanced decisions, creating eco-friendly designs, and reducing the environmental impact. In the construction industry, the impacts occur at different stages, such as manufacturing, processing, functional use, and disposal of building

materials at the end of their life cycle. When using steel, concrete, and wood structural components in any form of construction, LCA introduced an assessment of the GHG emissions and the consumption of embodied energy during the initial stage (Samad & Yahya, 2016).

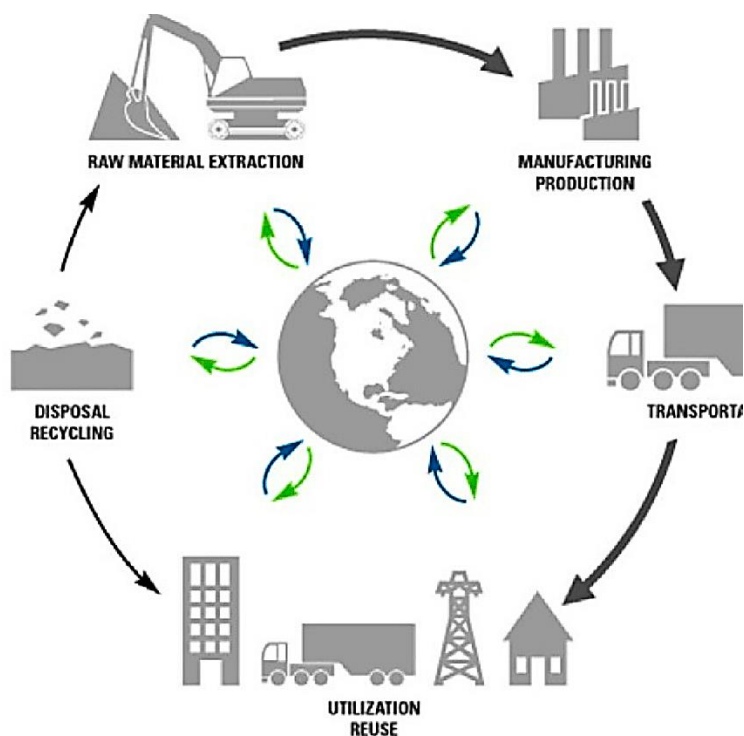


Fig. 10. Life cycle assessment of building materials

Source: Fenner and Kibert (2017).

DISCUSSION

The success of the green sustainable concept depends not only on its materials but also on the methods of construction. In this section, the method of adoption and growth of green vegetative matter over the roofs and walls of buildings are discussed. Growing vegetation along with the buildings provides many essential benefits such as cooling and insulation, production of clean air, reduction of rainwater runoff, energy savings, as well as a joyful and stress-reducing environment for the occupants. A green roof is an innovative type of roof surface that is flat or pitched in nature with vegetation over a waterproof membrane. These green roofs are created in a simple and basic way by using vegetative matter a few inches deep and can establish a mini park-like setup with trees, plants, and recreation facilities for people to use (Cantor, 2008). The green walls are constructed on vertical building elements on the interior and exterior, which provides the support of vegetation root growth in stacked pots. These walls are constructed with green vegetation and are becoming popular due to their design, including benefits such as sound insulation and circulation of clean air. The walls may be designed in the form of outdoor courtyards and indoor lobbies. A hotel building was constructed with a green roof and walls. In terms of economic benefits, green roofs save energy required for heating and cooling and extend the life cycle of the roofs by two to three times (Fig. 11). It also provides opportunities to urban citizens

in terms of food production and enhances the biodiversity with the physiological benefits of nature. The latest research conducted by Michigan University reveals that a 21,000 square feet area of a green roof can save around \$200,000 in energy costs during its whole service period. Typically, green roof construction can save between 15% and 25% of energy during summertime in two to three-storey buildings.

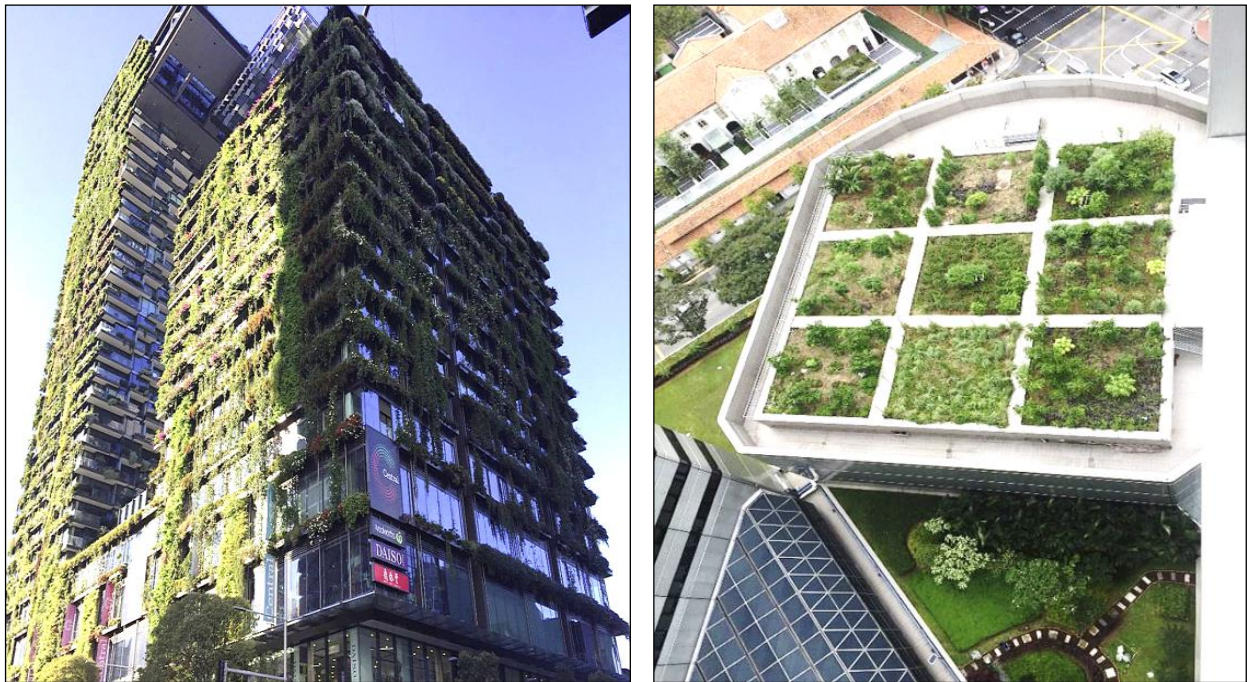


Fig. 11. Hotel buildings constructed with green walls and roofs in Singapore

Source: Beecham and Razzaghmanesh (2019).

Constructing green roofs may substantially increase the weight of the roof, and the roof can hold lots of precipitation, including rain, ice, and snow. The factors that affect the appearance and performance of a green roof are the amount of sunshade, climate, and the reflection of glass from other buildings. A green roof has the possibility to capture 40–60% of stormwater during rainfall, and it considerably decreases the flow rate into storm sewers. The green roofs lead to a 65% reduction in peak flows and a 55% reduction in runoff volumes during monsoon season. Quality water is needed to enable green walls to flourish for a long period via irrigation. Drainage is another important key to prevent clogging and to ensure the gardens do not become saturated. In terms of air pollution, a green roof is capable of reducing particulate matter of $10 \times 10^{-3} \mu\text{m}$ in diameter and can save 8,300 kWh of energy annually (Yildirim et al., 2020). In extreme climates, a green roof environment provides facilities for agriculture in the form of rock gardens. Green roof technology is mostly adopted in areas which have a denser population and in productive landscapes due to the development of urban environments. In suburban areas, the green wall technique is used in homes as a part of aesthetic enhancement to treat domestic wastewater and improve the response of nature in individual dwellings (Kalpana & Mohith, 2019). Green roofs are generally categorised into two categories: intrusive and extrusive. In the intrusive type of construction, the depth of the green profile ranges from 20 cm to 100 cm in depth. Due to this, the volume of area for holding water and root development is increased, and it leads to the growth of a variety of plants.

This type of roof wall requires less maintenance than ordinary flower gardens. In the extrusive type, the depth of soil contains a lean profile and has environmental benefits such as deeper and intensive green roofs. These types of roof constructions are suggested mostly in areas with desiccating winds and drought conditions.

In certain conditions, green walls may behave as a freestanding structure or as a building's main structure able to support cables, trellises, and frames. Due to the cover of vegetation, green roofs have low thermal mass; hence, the rate of thermal conductivity between the interior and exterior is greatly controlled. In green roofs, the soil and vegetation cover acts as an insulating layer and provides significant shading and thermal insulation to the building (Klemm & Wiggins, 2016). The amount of insulation is dependent on the type and extent of vegetation and the thickness of the growing medium. The soil used in green walls and roofs has the ability to absorb noise emitted from trams, trains, trucks, and buses. Compared to conventional concrete roofs, a 100-millimetre-thick green roof can reduce the transmission of noise by up to 5 dB. The durability of roofs and walls is based on the integrity of waterproof membranes, and the membrane can be protected by less exposure to direct sunlight, which protects against ultraviolet radiation and helps maintain constant heating and cooling of the membrane (Spiegel & Meadows, 2012). Due to the continuous presence of moisture, green roofs and walls offer good fire resistance. Plant selection and long-term maintenance of vegetation are essential to enhance the lifespan of the structure.

FUTURE SCOPE AND RECOMMENDATIONS

The future scope and recommendations for green sustainable construction, as explored in the article, emphasise advancing the field while addressing current challenges. Here are five key points:

- There's a growing need for advanced research in eco-friendly building materials. Future studies should focus on innovating and testing new sustainable materials, emphasising their durability and cost-effectiveness.
- Integrating cutting-edge technology like AI and IoT in green construction can optimise resource usage, enhance building efficiency, and monitor environmental impact.
- Developing and implementing comprehensive policies and regulations that encourage green construction practices is crucial. This includes incentives for using sustainable materials and constructing energy-efficient buildings.
- Increasing public awareness and education about the benefits of green construction can drive market demand. Educational programs and campaigns can play a vital role in changing perceptions and encouraging sustainable practices.
- Encouraging collaboration between government bodies, construction companies, material suppliers, and academic institutions can foster innovation and spread best practices in green construction.

CONCLUSIONS

In addressing green sustainability in construction, this conclusion emphasises the importance of zero energy consumption, the use of low carbon footprint materials, and reducing the overall impact on the environment. Key takeaways include:

- Zero energy consumption is pivotal in green construction, necessitating a balance between reducing greenhouse gas emissions and managing embodied energy in building materials.
- Emphasis on materials with low carbon footprints, such as earthen and wood-based products, is crucial for minimising environmental impact.
- A comprehensive framework incorporating social, environmental, and economic aspects is essential for achieving true green sustainability in construction.

- Life cycle assessment (LCA) plays a critical role in evaluating material impacts on the environment, offering a quantitative approach to sustainable material selection.
- Innovation, research, and development are key drivers in the field of green-sustainable construction, with LCA effectively meeting these challenges.
- Selecting construction materials not only affects environmental sustainability but also impacts the health and comfort of building occupants.
- Active involvement of both government and private sectors is necessary to implement and promote green sustainable construction practices.
- Educational initiatives and certifications in green sustainable materials are important for fostering awareness and advancement in environmental sustainability.

Authors' contributions

Conceptualisation: P.D., D.S.V. and A.S.; methodology: P.D. and D.S.V.; validation: A.K. and W.S.; formal analysis: A.S. and S.K.; data curation: P.D.; writing – original draft preparation: P.D.; writing – review and editing: D.S.V., A.K. and W.S.; supervision: D.S.V.

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

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IMPLEMENTACJA ZIELONYCH ZRÓWNOWAŻONYCH ROZWIĄZAŃ W INFRASTRUKTURZE

STRESZCZENIE

Celem artykułu jest przedstawienie zagadnień budownictwa zrównoważonego. W artykule wskazano, jakie jest znaczenie samego projektu architektonicznego, doboru materiałów i wyboru optymalnej konstrukcji budynku. W pracy wykorzystano badania literaturowe, wzbogacone przykładami zrealizowanych budynków. W badaniach wykazano istnienie głównych typów konstrukcji, które zrewolucjonizowały koncepcje zrównoważonej infrastruktury zielonej: konstrukcję z wykorzystaniem lekkiego szkieletu, konstrukcję z wykorzystaniem systemów okładzinowych, konstrukcję z autoklawizowanego betonu komórkowego (AAC), konstrukcję z ubijanej ziemi, konstrukcję z beli słomy. Autorzy zwrócili również uwagę na konieczność zrównoważonego zarządzania materiałami w budownictwie z uwagi na ograniczone zasoby surowców naturalnych. Głównym wnioskiem z przeprowadzonych badań jest konieczność kontrolowania zanieczyszczeń pochodzących z sektora budowlanego, co jest niezbędne dla ochrony środowiska naturalnego i zachowania zasady zrównoważonej gospodarki.

Słowa kluczowe: budownictwo zrównoważone, przyjazny dla środowiska, zanieczyszczenie, materiały ściennie, środowisko mieszkaniowe

DEVELOPMENT OF ADVANCED SOLAR PANEL TECHNOLOGIES IN BUILDINGS – A REVIEW

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ABSTRACT

In recent years, the global energy landscape has been undergoing a significant transformation, with renewable energy sources gaining prominence. Among these, solar energy has emerged as a leading ‘green energy’ option, particularly in India, which is at the forefront of this renewable energy revolution. This article focuses on the increasing relevance of solar energy, underlined by the widespread adoption of solar power in various sectors, including residential, commercial, and industrial. The centrepiece of this solar energy boom is the solar panel, primarily installed on commercial buildings, which harnesses solar energy and converts it into electrical power. These panels are composed of a network of solar cells, each crafted from layers of silicon, phosphorous, and boron, meticulously arranged to optimise energy absorption and conversion. The paper delves into the technological progress in the field of solar panel systems, emphasising their growing integration in different types of buildings. It discusses how these advancements not only enhance energy efficiency but also contribute significantly to the development of a more sustainable and environmentally friendly energy future. The article presents a comprehensive overview of the current state of solar panel technology and its potential implications for shaping a greener energy landscape.

Keywords: solar panel, passive buildings, green energy, sustainability, renewable energy

INTRODUCTION

In recent years, solar energy has emerged as a notable renewable energy source. This surge in popularity is evident in the increasing adoption of it by residential, commercial, and industrial sectors, driven by its environmental sustainability (Vaverková et al., 2022; Vijayan et al., 2023). Often referred to as photovoltaic energy, solar power has seen a significant rise in installations, with a record 760 GW reached globally in 2020, including 139 GW added in that year alone. This growth coincides with advancements in solar technology and a shift in focus from traditional energy sources like coal and oil. Zander (2021) conducted a study in Darwin to analyse the usage patterns and the effectiveness of feed-in tariffs (FITs) in promoting domestic solar power production. The study aimed to identify barriers to solar panel adoption despite attractive incentives and to determine the average installation cost under the FIT scheme. A survey involving 652 respondents revealed that the primary deterrents were high installation costs, decreasing efficiency and storage capacity over time, and a 10% annual decline in interest in purchasing solar

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panels. The research indicated that an average FIT of 14.40 cents per 1 kWh was necessary, contrasting with the current subsidised rate of approximately 9 cents per 1 kWh (inclusive of goods and services tax), which falls short in offsetting additional battery expenses. The study also found that 40% of users with a 30% reliance on solar energy and 17% with a 60% dependence might discontinue using solar power if the existing policies were not revised. Solar panels have become increasingly significant in the construction industry due to their ability to provide sustainable and cost-effective energy solutions. Their integration into building designs, known as building-integrated photovoltaics (BIPV), not only reduces the carbon footprint of buildings but also enhances their aesthetic appeal. Solar panels contribute to the energy efficiency of buildings, lowering operational costs and increasing property value. Additionally, their use in construction aligns with global trends towards green building practices and helps in meeting environmental regulatory standards. This adoption signifies a critical step towards a more sustainable and eco-friendly construction sector.

Tarsitano, Ciancio and Coppi (2017) presented a study exploring the use of solar-powered absorption systems for air conditioning in residential buildings, emphasising the shift from non-renewable energy sources. The research involved a selected group of households to evaluate the efficacy of this technology in terms of energy savings, return on investment, and reduction in carbon emissions. The results of the study indicated that these solar-driven absorption air conditioning systems not only surpassed the performance of traditional methods but also contributed positively to environmental sustainability by utilising a limitless source of clean energy. Teodorescu and Vartires (2016) described the use of photovoltaics combined with thermal structures for domestic constructions with the help of TRANSOL software and EN 15316-4-3:2014 methods for simulation. In the beginning, solar voltaic usage was measured for domestic hot water (DHW) preparation and electrical and thermal requirements. The evaluation was performed on a combined structure of DHW and heating for its properties and solar fractions. The analyses were strictly made using TRANSOL and EN 15316-4-3:2014 standards (European Committee for Standardisation [CEN], 2014) and later compared with each other to get an optimal value. Saleheen Salema, Islam, Sarimuthu and Hasanet (2021) conducted a detailed study to validate the effectiveness of a goal-oriented prototype in the real-time operation of a 232.5 kWp grid-connected photovoltaic (GCPV) system, aimed at establishing a sustainable infrastructure for business operations in Malaysia. This research involved a comprehensive analysis to assess the performance and viability of the GCPV system in an actual business setting, demonstrating the practical application and scalability of solar energy solutions in enhancing the energy infrastructure within the region. The study underscores the potential of PV systems in contributing to the renewable energy landscape, particularly in commercial and industrial applications, by providing a reliable source of clean energy.

Oh and Son (2020) introduced a novel approach to designing community solar photovoltaic (PV) service plans for commercial buildings, aiming to achieve a harmonious balance between benefit, equity, and fairness. Utilising the Lagrangian relaxation and dual ascent methods, they iteratively found the optimal solution that enhances fairness in service distribution by up to 51% compared to strategies focused solely on maximising benefits. This methodology allows for a detailed breakdown of the advantages and equitable aspects of various service models, providing valuable insights for the development of community PV services that are both efficient and fair. This research highlights the importance of considering equity in the deployment of renewable energy solutions, ensuring that the benefits of solar energy are accessible and distributed fairly among all stakeholders. Sivaram, Premalatha and Arunagiri (2021) explored an innovative integration of passive solar energy techniques with PVs within the context of the CMS solar-powered greenhouse program. Their study introduced a solar still, a device designed to achieve multiple functions including air ventilation, energy generation, and water purification, all within a structural model. This model significantly reduced the airflow inside the structure by 30% during peak sunlight hours, aligning with the ANSI/ASHRAE Standard 62.1-2010 for indoor air quality and utilising GRIHA software to demonstrate its commercial feasibility. They further developed this method by adjusting the ductwork

to utilise the thermal energy captured by the solar still to enhance air ventilation. This approach not only showcases the multifunctional benefits of incorporating solar energy into building designs but also emphasises the system’s adaptability and potential for commercial application. The physical layout and satellite view of Monash University Malaysia, where this system was presumably tested or exemplified, are provided to illustrate the practical implementation of these concepts and are depicted in Figure 1.



Fig. 1. Monash University Malaysia’s physical layout and satellite view

Source: Saleheen et al. (2021), CC BY-SA 3.0.

Liu, Yue, Lu and Li (2021) explored the impact of dust accumulation on PV panels in Wuhan, China, examining both the origins and development of dirt particles as well as their effects on the panels’ efficiency. The study found that dust primarily originates from industrial emissions and urban pollution, including materials like sand, stone mortar, and dolomite, transported through the air and deposited on the panels. This accumulation of dirt reduces the panels’ ability to transmit light, thereby decreasing their efficiency. The findings underscore the necessity for developing effective and sustainable methods for cleaning PV panels to maintain their performance.

Sheps, Golovinsky, Yaremenko and Shchukina (2021) investigated a novel passive solar panel technology that enhances energy generation by using thermal collection on the outer walls of buildings, specifically under the climatic conditions of central Russia. This approach allows for the conversion of absorbed solar energy into usable power, significantly improving a building’s energy efficiency. The study also introduced a simplified computational model for analysing heat transfer dynamics in passive solar panels. By applying the principle of superposition of thermal waves, the research offers insights into optimising the thermal management of buildings to maximise solar energy utilisation. This advancement in passive solar technology presents a promising avenue for enhancing the sustainability and performance of energy systems in buildings.

Noorollahi, Khatibi and Eslami (2021) conducted a study to explore the feasibility of replacing natural gas with solar and wind energy at a national level, employing simulation techniques. The findings highlighted that all the methods investigated resulted in a significant reduction of carbon dioxide emissions, primarily due to the decreased consumption of natural gas. The study revealed that employing heat pumps to generate electricity from solar or wind sources led to an increase in the average total cost by approximately 127% and 326%, respectively. However, the use of solar thermal collectors was found to reduce the average total cost by about 13%. Given the existing natural gas infrastructure in Iran, the study concluded that the adoption of solar thermal collectors presents a viable and efficient alternative.

RESIDENTIAL BUILDINGS

In the context of residential buildings, solar panels play a pivotal role in promoting sustainable living and energy independence. They not only reduce electricity bills but also contribute to a greener environment by harnessing renewable solar energy. Sim and Suh (2021) conducted a study to assess the economic impact of integrating solar cells and ground source heat pumps (GSHP) in residential campus buildings in Korea. Recognising the significant energy-saving potential in these structures, the research aimed to optimise the life cycle cost (LCC) using DesignBuilder and EnergyPlus simulation tools. The study encompassed a comprehensive evaluation of various costs and impacts associated with the use of solar cells and GSHP. For practical insights, a residential case study in Korea, where seven experimental prototypes were examined, was selected. The analysis of these models provided a framework for the adoption of energy-efficient solutions tailored to specific conditions, highlighting the feasibility and benefits of such integrated systems.

Application

Fikru (2020) demonstrated the factors of reducing bills for consumers with domestic photovoltaics in four US states with the help of prototypes. The analysis was made through the prototypes considering their state situation, local rules, and the building's properties. The observation showed that higher savings were achieved with favourable policies to locate solar cells in areas with a greater potential for photovoltaic penetration, and areas with zip codes encouraging small-scale installations have much more savings during summer. The outcomes reveal that liberal policies to promote the use of solar panels are most effective. In conclusion, various factors that have an impact on electrical savings were discussed. Wang, Zheng and Cheng (2021) reported a testing method for the adoption of solar power to prepare hot water on a large scale, considering its environment-friendly approach in the domestic houses of China. The solar hot water system (SHWS) can reduce the dependence on conventional energy sources by 20%. An adaptability calculation prototype was prepared to find eight stable and six dynamic energy, and environmental impact characteristics. The observation showed that the primary focus subjects are solar radiation, solar fraction, installation area, payback period, and water supply temperature. Only a 25% change in the analysis index has little or no impact on the final result. The energy-economic-environment adaptability analysis method is the most trustworthy. The result also gave many vital points to encourage the adaptability of renewable sources of energy. Figure 2 illustrates an unglazed transpired solar collector system in operation.

Panagiotidou, Aye and Rismanchi (2021) investigated the optimal cost and zero-total emission goals for multi-residential optimised retrofitted buildings. The aim was to help achieve the greenhouse gas (GHG) goals of the European Union under the European Green Deal. An optimisation method with multiple targets was created to reduce GHGs and life cycle prices. A building was chosen to analyse the model in four climatic areas in Greece. The outcomes revealed that optimal retrofit is at par with required market trends like the solar thermal receiver and air-to-air heat pumps and covered the insulation with a 60–96% reduction in GHG production depending on the envelope layer. With the improvements in factors like photovoltaic-thermal systems, cooling systems, heat pumps, and facade-combined photovoltaic structures, a promising future with net-zero GHG emissions is anticipated. Alsabbagh (2019) reported the general outlook on photovoltaics on residential buildings on an island. The research was conducted to improve the natural renewable power plan by integrating solar panels to encourage renewable power. An online study included 764 answers collected from questionnaires from the general public. The response showed that the majority are happy with the solar cell equipment but are reluctant to adopt it because of its high cost, lack of proper knowledge, and shorter lifespan. The paper describes the role the government still needs to play to make this project a success. Li, Mojiri, Rosengarten and Stanley (2021) proposed a suburban demand-side administration with the help of a combined thermal depository and solar-driven heat pump. The aim is to find solutions to connection overload and voltage issues when extra solar-generated current is passed to the mainline. An Australian building was chosen to find hourly domestic boiler

and thermal loads for a year under a simulation of the building's power. The data were collected and compared with electric sub-meters to find the average heat storage capacity, heat pump requirement, and export of solar structures. The outcomes reflect around a 45% reduction in temporal shifts, an 84% increase in hot water loads and air-conditioning, and a reduction in grid electricity demand by 76% when using a 5-kW photovoltaic structure. The conclusion was that this suggested method efficiently addresses damages in the electricity grid due to photovoltaics without compromising electricity requirements.

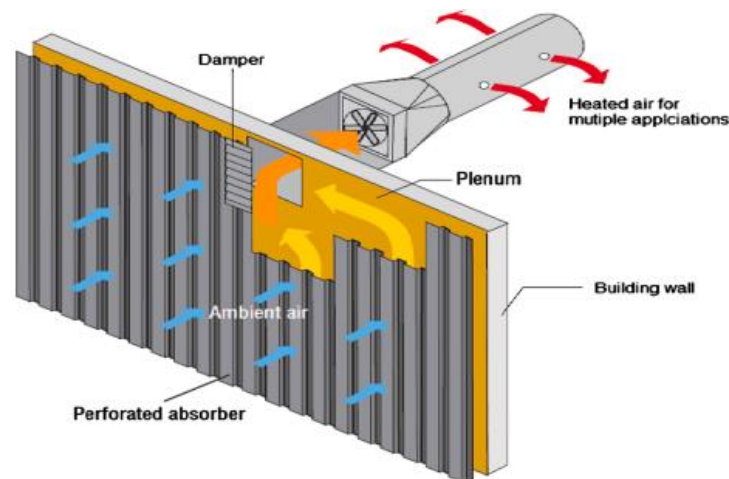


Fig. 2. An unglazed transpired solar collector system in operation

Source: Saini, Paolo, Fiedler, Widén and Zhang (2021), CC BY-SA 3.0.

Panagiotidou, Aye and Rismanchi (2020) described a method of solar-powered boiler systems for Mediterranean places among medium-rise domestic constructions. The limited roof availability of these houses was aimed to be addressed with solar-powered boiler systems at par with present electric boilers. A proper analysis was made on S4 combined heat pump boiler and solar cells, S3 electrical backup solar PV/T boilers, S2 backup thermal solar water boilers, and S1 solar PV water boilers. The outcomes were compared with net LCC and yearly electricity from the power grid for 20 years. The S3 and S4 showed higher current production but were subjected to a high-cost setup, while LCC was found to be minimal, with S2 in colder places and S3 in hotter areas.

Zander (2020) prepared a report on new opportunities for household solar cells in Australia. Past usage and future prospects of using solar cells were considered to find the possible reluctance to use them, with 1,126 people in Australia being chosen for an online questionnaire. The answer revealed that 65 out of 100 people with no previous solar panels were eager to adopt it despite past or future trends. Most renters and homeowners are unsure about using solar PVs because of their uncertainties in maintenance, adoption costs, and future profits. However, they are aware of its environment-friendly aspects. The conclusion was that a uniform system must be regulated to provide proper profit benefits to consumers to provide the much needed and cheaper source of electricity, especially in city areas.

Abd-ur-Rehman, Sulaiman, Mehmood, Shakir and Umer (2018) demonstrated the importance of manufacturing clean energy through photovoltaics and the possibilities of power savings in the suburban houses of Saudi Arabia. A modified International Energy Conservation Code (IECC) building was chosen to simulate its energy outcomes, storage, and usage methods. The products showed 27% less power used by appliances, 46% less for ignition, 37% less for a room heater, and 56% less for cooling in the IECC compared to an average house. Further, when solar boilers and solar cells connected to the power grid were added secondarily, a 76% reduction in the bill was seen.

The paper concluded that with lucrative subsidies by the government, this innovative source could be appropriately utilised, and all its prospects can be explored.

Asrami, Sohani, Saedpanah and Sayyaadi (2021) studied the eminent way to use solar cells in suburban constructions. The environmental impact, economic aspects, and energy were considered to compare the three frameworks of full feed-in and grid connection with or without batteries. Each framework was further explored using the TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) and the NSGA-II (Non-Dominated Sorting Genetic Algorithm II). The proposed method was evaluated in a suburban house situated in Teheran. The outcomes showed the entire feed-in process to be most effective, with \$0.15 per 1 kWh of levelised price, a payback time of 7.3 years, and a massive 78.6% improvement in performance ratio; however, it has inevitable setback to human health (0.023 DALY), the ecosystem (0.101 species per year) and destruction of resources (\$487 per year).

Chahartaghi and Baghaee (2020) investigated the economic and practical aspects of integrated heating, cooling, and power systems established on amalgamated micro gas turbines (MGT) for suburban constructions. A simulation of the combined cooling, heating, and power (CCHP) model on MGTs was made to collect the early function of the cycle in reality. Solar cells were included to boost the MGT's heat cycle, parabolic solar dishes, heat-saving vapour generation, auxiliary boiler, and microturbines in the system. The observation was made by changing the number of system parts. A levelised cost of electricity (LCoE) was also found for the best performances, and the economic situations were also evaluated. In the end, the LCoE of the system was differentiated from the LCoE of the solar cell structure.

Saini et al. (2021) demonstrated an evaluation of the practical-economic condition of an exhaust air thermal pump structure based on porous transpired solar receivers situated in colder areas. All parts and systems were strictly examined for varied solar collector sizes. An algorithm was made to control airflow inside an unglazed transpired solar collector (UTSC), and a comparison was made from traditional flow control. The TRNSYS model was used to procure the exhaust air heat pump (EAHP) maximisation of multi-storey constructions, and the UTSC model was used to collect data about energy and capabilities. The outcomes revealed that the UTSC is a better method to control airflow for improving periodical performance with huge savings. Wu and Skye (2021) devised a review system of successful net-zero power-consuming buildings throughout the world. The net-zero energy building (NZEB) with renewable power sources of wind, biomass (with a combined heat and power system), solar thermal, and photovoltaics were examined. Energy storage options, hydrogen storage, district cooling/heating systems, and electrical grids were reviewed. The power efficiency and future independence were checked. Modern envelope design buildings, heating, ventilation, and air conditioning (HVAC) systems, and new boiler systems were proposed along with other adaptability features that can be considered according to climate conditions. This paper provides detailed information about the improvements in net-zero power-consuming houses and some measures to encourage their adoption.

Zakeri, Cross, Dodds and Gissey (2021) explored strategies to maximise profits from household-owned solar panels and storage batteries. Their study focused on the growing adaptability and advancements in photovoltaic (PV) technologies, propelled by various government and non-government initiatives, which have opened up new revenue streams for homeowners through excess energy generation. The research proposed several policies aimed at enhancing the financial returns from PV investments. These included dynamic retail pricing to capitalise on domestic storage capacity, a feed-in tariff bonus, and an energy storage policy that offers rewards when additional electricity is supplied to the grid. By integrating a national energy system model with a cost-optimising consumer model, the effectiveness of these policies was assessed. The findings indicated that the PV self-consumption model could yield up to a 70% return on investment, while the energy storage policy could offer up to a 40% return, assuming a one-third reduction in costs and without the need for additional facilities. The study concluded that dynamic electricity pricing and optimal storage deployment are crucial for maximising financial returns from solar energy investments. Qiu, Kahn and Xing (2019) described the calculated recoil effects of domiciliary applications of solar panels. Two hundred seventy-seven houses with solar panels and 4,000 ordinary houses were chosen around Phoenix

(Arizona) to take hourly data from them using their electricity meter and solar generation meter. These houses were studied adequately for four years (2013–2017). The results showed that, with an increase of 1 kWh of solar energy creation, the household consumes 0.18 kWh more than the average total consumption. The findings thus showed an 18% solar recoiling effect with an additional annual income of \$972 because of the usage of solar panels.

Experimental studies

Sharma (2021) prepared research on general users' perception of using personal solar water boilers in the city of Phoenix. The study was conducted to find the market capabilities of solar boilers in the US and the possible reasons for their usage/non-usage. The survey focused on collecting data on solar boiler awareness, family income, and educational status to target future consumers. The survey revealed that people with family incomes above \$60,000 and higher qualifications are users of solar boilers and are ready to accept other eco-friendly solar cell-powered technologies. 70% of people were found to be aware of the importance of photovoltaic cells. This research thus proved essential to ventures selling solar water heaters in the USA to find potential users and frame their marketing strategy. Bandyopadhyay, Leibowicz and Webber (2021) discussed the apex grid impact of load, grid power usage, and discharge in suburban houses using various pairs of distributed power technologies at different price levels. Some places using intelligent thermostats, chilled thermal power vaults, Li-ion batteries, and solar cells were chosen to apply a functional framework for reducing current charges, operational prices, and amortised capital for one year. The observation showed that the only obstacle to the acceptance of energy and environment-friendly solar cells is the higher price of storage units. Furthermore, pricing mechanisms decide the popularity of the two storage units among houses. In the end, the suggestion to use an efficient apex load control mechanism with lucrative returns for promoting storage units among households with demand charges was proposed.

Rosato Ciervo, Ciampi and Sibilio (2019) conducted a study on a novel centralised hybrid solar district heating system, integrating solar power with seasonal borehole thermal energy storage. This study, leveraging dynamic transient system simulation software TRNSYS over a five-year period, assessed the system's potential to reduce primary energy use, carbon dioxide emissions, and operational costs when compared to conventional heating systems. The inclusion of photovoltaic thermal (PVT) collectors, notable for their ability to generate both electricity and heat, showed a significant impact on reducing the system's carbon footprint and energy consumption. Specifically, the use of PVT collectors led to a notable decrease in carbon dioxide emissions, energy supply costs, and operational costs over five years, attributed to the enhanced median temperature at the PVT collectors' entry point, albeit with a slight reduction in their electrical efficiency. This approach exemplifies how integrating renewable energy sources with advanced thermal storage technologies can offer a sustainable and cost-effective alternative to traditional district heating solutions. Pinamonti and Baggio (2020) examined the effectiveness of solar-assisted heat pump (SAHP) systems paired with energy storage solutions across a variety of applications, including both heating and cooling, within three buildings of differing energy performance levels. They found that increasing the temperature of the thermal storage by 10°C in combination with solar thermal (ST) collectors proved beneficial across all cases studied. The use of solar thermal collectors emerged as the most favourable strategy, characterised by reduced energy demand and cost efficiency. The findings of this investigation are particularly relevant to specific climatic conditions, suggesting that the applicability and performance of SAHP systems can significantly benefit from integration with solar thermal technologies, highlighting a sustainable approach to managing a building's heating and cooling needs. Qiu, Wang and Xing (2021) leveraged a unique and previously untapped dataset detailing customer-specific electricity needs and the deployment of solar panel systems. Their study focused on three key areas, including an empirical assessment of the impact of deploying solar panels in non-residential settings. They found that the reduction in electricity purchases from the grid was significantly less when compared to the generation of solar power, highlighting the efficiency and environmental benefits of solar energy adoption. The concept of "solar rebound effects" was introduced as a crucial metric for assessing the environmental advantages of solar power utilisation.

Krarti (2021) explored the energy efficiency of dynamic overhangs combined with photovoltaic (PV) arrays on windows in U.S. residential buildings, specifically analysing their impact in Golden, Colorado. The study revealed that dynamic overhangs could reduce energy demand by up to 6% without PV arrays and by over 35% when integrated with PV panels, based on monthly calculations. These dynamic overhangs, especially when used with PV arrays, offer significant energy savings by adjusting to solar exposure, thereby enhancing the overall energy performance of homes. This approach suggests that incorporating dynamic overhangs with PV technology can significantly reduce a home's energy requirements, offering a sustainable solution to energy consumption challenges in residential settings.

COMMERCIAL BUILDINGS

For commercial buildings, the integration of solar panels is a strategic move towards energy efficiency and corporate responsibility. These installations not only significantly cut down energy costs but also demonstrate a commitment to sustainable practices, enhancing the company's public image. Suhail, Akhtar and Kirmani (2021) discussed the economic analysis of a 26 kW PV method and demonstrated the economic comparison between a grid-connected PV process and a stand-alone PV method. Solar power is a pure and consistent source of power, and its atmosphere-friendly nature provides it an edge over the other renewable sources of power. The performance of the PV method is higher in January and December, while it is lower from April to July. The current evolution in PV methods is advantageous for meeting the power required, particularly in metropolitan areas. Behzadi and Arabkoohsar (2020) described a novel creation of intelligent building energy systems. In the system, photovoltaic thermal (PVT) panels are connected to a heat storage tank to provide a large portion of the structure's heat and electricity requirement. With such a method, not only may the share of reusable power in the national power matrix safely rise, but also the building will profit from the cheap, eco-friendly power flows generated by itself. The outcomes show that the process provides the total annual domestic hot water demand and creates 402.8 m³ of hot water at 40°C to be sold to the regional district heating system.

Mendecka, Tribioli and Cozzolino (2020) conducted research on the environmental impact of a standalone solar-based polygeneration power system, which includes a photovoltaic array, battery storage, a unitised regenerative polymer electrolyte fuel cell, and a diesel generator as backup. The study highlighted the minimal initial but significant lifecycle environmental impact of the regenerative fuel cell. The findings suggest potential improvements in system design to reduce reliance on batteries and diesel generators, thereby enhancing the sustainability of the building operation and usage phases. This research underscores the critical role of construction and operational phases in influencing both the energy supply and demand, despite the minimal contribution from the end-of-life phase.

Christiaanse, Loonen and Evins (2021) examined the economic feasibility of solar panel installations on rooftops from the perspective of manufacturing companies and the availability of structural frameworks. They developed a two-tier optimisation model to streamline the design process for rooftop PV systems. This model enables high-level adjustments to design parameters, aiming to cut costs or adjust priorities in lower-tier optimisations. Such adjustments, which focus on reducing installation costs and optimising energy imports from the grid, hinge on the demand profile of the building. The innovative approach of modifying PV system design parameters not only maximises energy efficiency in smaller structures but also significantly boosts potential energy export, tripling the maximum energy intake from the grid. This methodological shift promises enhanced energy output with optimised costs, marking a step forward in the integration of solar energy into urban infrastructure. Drissi, Ling and Mo (2020) explored the development of an innovative core-shell phase change material (PCM) known as AGGSpcm, designed to capture and store solar energy within the structural envelope of buildings for heating and cooling purposes. By enhancing the concentration of microencapsulated PCMs (mPCMs) within the AGGSpcm or selecting a PCM with an optimal phase change temperature,

the study achieved improved thermal storage and release efficiency. The results demonstrated significant enhancements in thermal performance and energy savings within concrete structures through the use of PCMs. The utilisation of these materials in construction contributes to substantial energy conservation, as illustrated by the integration of the solar energy system into a building's design, depicted in both schematic and photographic formats. This approach not only optimises the building's energy efficiency but also represents a forward step in sustainable architectural practices. Figure 3 shows the solar energy system integrated into a building, which is illustrated schematically and photographed.

Mendecka et al. (2021) developed a concept for a hybrid renewable power plant incorporating a novel integration of photovoltaic panels with unitised solid oxide fuel cells powered by bio-gas. This approach enables the power plant to operate entirely on renewable energy, assuming the bio-gas digester produces between 6,000 to 9,500 standard cubic meters per year and the system's battery storage starts the year fully charged. This innovative design represents a significant step forward in sustainable energy solutions, offering a blueprint for achieving 100% renewable energy operation in power generation. El-Bayeh Alzaareer, Brahmi, Zellagui and Eicker (2021) introduced a new multi-criteria decision-making algorithm that prioritises efficiency over the traditional Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This algorithm, based on a rank weight system, speeds up the selection process of solar panels by evaluating various criteria. The findings challenge the assumption that the most expensive solar panels are automatically the best choice, or that the cheapest options are the least desirable. By employing this refined decision-making process, stakeholders can make more informed choices regarding solar panel selection, emphasising the balance between cost and performance without assuming a direct correlation between price and quality.

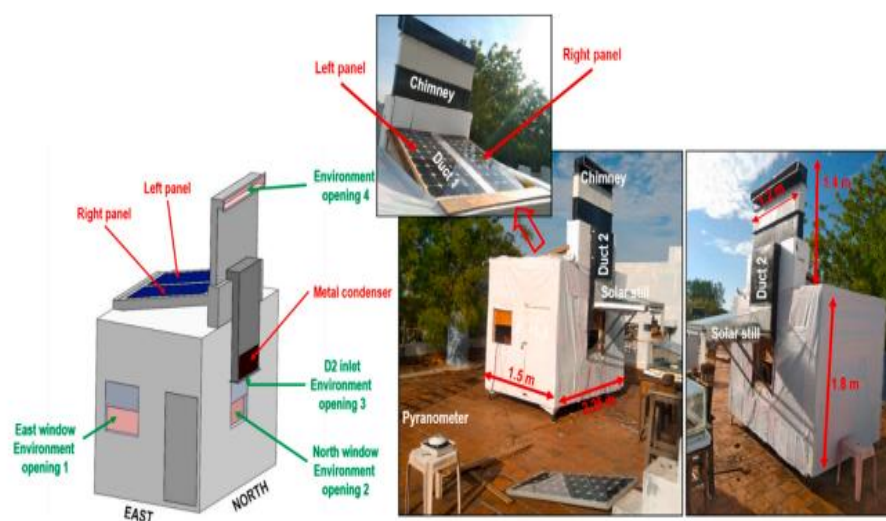


Fig. 3. The solar energy system integrated into the building

Source: Sivaram et al. (2021), CC BY-SA 3.0.

Elghamry Hassan and Hawwash (2020) conducted a parametric analysis on the impact of integrating solar cells within the building envelope, focusing on generated power, energy consumption, temperature regulation, and carbon dioxide emissions. Utilising design-builder software and validated through experimental data, the study found that solar cells positioned within windows had the least effect on light transmittance, while those oriented northward minimised carbon dioxide emissions most effectively. Installing solar cells on the façade and roof was shown to significantly reduce annual energy consumption by approximately 15% and 40%, respectively,

compared to buildings without such installations. Bre, e Silva Machado, Lawrie, Crawley and Lamberts (2021) undertook a comprehensive investigation to assess the accuracy of solar radiation data incorporated into Typical Meteorological Year (TMY) databases for various Brazilian locations. This study highlighted how the quality of solar radiation data influences the selection of months for TMYs and, consequently, the outcomes of Building Performance Simulations (BPS). Their analysis revealed that commercial buildings are more susceptible to inaccuracies in weather data than residential buildings, especially concerning cooling load forecasts. By comparing the global horizontal irradiation data from the latest Brazilian TMY databases with satellite-derived data, the research underscored the critical importance of accurate solar radiation models in influencing TMY compilations and, by extension, building energy simulations.

INDUSTRIAL BUILDINGS

In the realm of industrial buildings, the integration of solar panels is increasingly recognised as a vital strategy for enhancing operational efficiency and advancing environmental sustainability. These systems provide a dependable and economical energy source, crucial for meeting the substantial energy demands typical of industrial operations.

Aly, Chokwiththaya and Poche (2017) explored the impact of aerodynamic features on the performance of solar panels mounted on gable roofs. Their study specifically focused on how various panel configurations could mitigate wind-induced forces on buildings, while maintaining aesthetic appeal and functionality for widespread application. Findings indicated that solar panels significantly reduce wind uplift on flat roofs and that strategically combining panels can lower wind pressures on buildings with minimal structural enhancements, ensuring reliable power supply, especially during power outages. Ayodele, Ogunjuyigbe and Nwakanma (2021) investigated the feasibility of meeting Ibadan's growing electricity needs through rooftop solar PV systems. Using advanced mapping technologies and GIS, they assessed the potential rooftop area suitable for solar installations, considering factors like shadowing to minimise energy loss. The study estimated that Ibadan could generate approximately 6.6714 TWh of solar energy annually, highlighting a significant potential for solar energy to contribute to the city's power supply with an estimated capacity of 1,734.8 MWp.

Pakere Lauka and Blumberga (2018) examined the integration of photovoltaic thermal (PVT) systems into district heating networks in European climates. This research aimed to identify the most effective ways to utilise surplus solar energy for heating purposes, balancing solar power generation against the energy and heating needs of buildings. The analysis showed that converting excess electrical energy into heat is economically viable, particularly when electricity prices are lower than those of district heating, offering a cost-effective method to enhance energy efficiency and sustainability in industrial settings.

These studies collectively underscore the critical role of solar energy technologies in transforming industrial buildings into more energy-efficient and sustainable infrastructures. By leveraging solar power, industrial facilities can significantly reduce their environmental footprint while ensuring energy security and operational efficiency.

ADVANCED TECHNOLOGY AND RECENT TRENDS IN SOLAR PANELS

This section explores groundbreaking advancements in solar panel technology, underscoring the enhancements in efficiency, cost-effectiveness, and versatility for architectural integration. These innovations represent significant strides in harnessing renewable energy more effectively.

Tian et al. (2021) conducted an examination of 13 different membrane materials, analysing their thermal and optical properties using the Perkin Elmer LAMBDA™ 750 spectrophotometer. The study addressed how these materials affect the indoor thermal environment, particularly focusing on their ability to absorb and transmit solar radiation. A model was developed to calculate the internal solar heat gain, providing insights into how different levels of light transmittance and absorptivity impact indoor thermal comfort. Yemenici and Aksoy (2021) undertook both

practical and numerical studies to assess the impact of wind direction and panel tilt angles on solar panel efficiency. Their findings revealed that the optimal tilt angle for minimising wind load while maximising energy capture varies significantly with wind direction. This research highlights the importance of considering environmental factors in the placement and orientation of solar panels to enhance their performance and durability.

Xu et al. (2021) developed a multi-dimensional analysis to evaluate solar power potential at the urban block level, utilising a clustering algorithm to categorise blocks based on morphological parameters. Their findings indicate a substantial variation in solar power potential across different block types, with building density identified as a key factor influencing this potential. As building density increases, so does the achievable solar power, demonstrating the impact of urban design on renewable energy generation capacity. Together, these studies illuminate the path forward in solar panel technology, emphasising the need for a nuanced understanding of environmental interactions and urban planning in maximising solar energy utilisation.

THE CURRENT IMPACT OF SOLAR PANELS

This section examines the broad-ranging effects of solar panel implementation in today's context. It addresses how solar panels are influencing energy policies, environmental conservation, and economic dynamics, signifying a major shift towards more sustainable and responsible energy use globally. Salehi, Jahanbakhshi, Golzarian and Khojastehpour (2021) suggested the connection between reducing the solar panel's temperature and variation in its energy and efficiency in discussions with general controlling situations and the ones furnished with thermoelectric modules. The process evolved in this study was made from two main parts known as cooling units and solar panels. The results reveal that utilising a thermoelectric module with a heater could enhance the efficiency and energy of solar panels by 10.50% each. The outcomes of this study showed that the industrial design of solar panels with a process to decrease excess heat from solar radiation could be helpful in increasing total efficiency via reducing extra heat and enhancing the panels' efficiency. Gupta, Dubey, Kumar and Mehta (2021) proposed an innovative approach to harnessing solar energy, focusing on the utilisation of the full spectrum of solar irradiation. They detailed the development and application of a hybrid solar photovoltaic and thermal (SPVT) system. This system uniquely combines a transparent solar panel with a primary Fresnel lens to concentrate sunlight efficiently. Their research found that using a red filter in the semi-transparent solar panel yielded better results than a blue filter, enhancing both the electrical output and thermal energy for domestic hot water production. This dual-functionality approach not only improves the efficiency and cost-effectiveness of solar energy systems but also contributes to the sustainable development goals by providing a more comprehensive and resilient energy solution.

Dermentzis, Ochs and Franzoi (2021) reported on a four-year monitoring project of two newly constructed multi-family apartments in Innsbruck, designed with the ambition of achieving net-zero energy building (NZEB) status. The primary objective for these NZEBs was to annually match the buildings' electrical energy consumption with the energy produced by on-site PV systems, thereby achieving a balance between energy demand and supply. This balance aims to reduce both the buildings' heating requirements and thermal losses, underscoring the importance of optimising the buildings' energy efficiency. The study highlighted the necessity of managing and reducing thermal losses and energy consumption as critical steps toward realising the NZEB goal. It demonstrated that achieving NZEB status requires careful planning and integration of additional PV panels and other energy-saving measures to ensure that the buildings operate efficiently and sustainably.

Wu et al. (2022) explored an innovative approach to solar energy generation by examining the integration of solar cells into building designs and the broader implications of such systems on energy production. Their research delved into the architectural incorporation of solar panels and the optimisation of solar energy output, utilising an extensive array of data sources and creating a supportive framework for the analysis. Solar energy, recognised for its environmental benefits and sustainability, stands out as a flexible and scalable source that overcomes geographical limitations and can be directly integrated into the local power grid through inverters. The study aimed

to address several challenges facing solar energy deployment, including issues related to system integration, capacity limitations, efficiency concerns, and the need for more comprehensive monitoring mechanisms. By focusing on these areas, the research contributes to enhancing the reliability, effectiveness, and scalability of solar energy solutions (Wu et al., 2022).

CONCLUSIONS

Solar energy is a free, clean, and sustainable source of energy. Energy usage per individual is increasing at an alarming pace. Energy prices are also reaching new highs. Buildings are being built with an eye on energy efficiency. The objective is to reduce energy consumption and to increase the use of alternative solar energy, which has many advantages.

- Solar-powered buildings are very effective in conserving energy in a variety of ways. By using cutting-edge solar energy technologies, buildings may save up to 35–45% on their energy use. Additionally, you may become a net-zero energy building owner if you generate more energy than you use. Without question, solar-powered buildings that make effective use of technology use less energy.
- Solar-powered buildings increase the efficiency of the heating and cooling system by 25% through the appropriate installation of a modern HVAC system. Solar-powered energy-efficient buildings may decrease the operating costs of a highly efficient solar water heater by 90%.
- When low-emissivity window glazing is used, it helps to decrease the demand for space cooling by about 35%. A light-coloured roof lowers the warmth of the roof since it absorbs less than 50% of the solar radiation.
- When energy-efficient lighting and appliances are utilised, a solar building may decrease its energy consumption by 15–25%. With the continuous advancement of construction technologies, achieving better energy efficiency in buildings is becoming simpler.

Authors' contributions

Conceptualisation: S.K., D.S.V., P.D. and A.S.; methodology: S.K., D.S.V., P.D. and A.S.; validation: S.K., D.S.V., P.D. and A.S.; formal analysis: S.K., D.S.V., P.D. and A.S.; investigation: S.K., D.S.V., P.D. and A.S.; resources: S.K., D.S.V., P.D. and A.S.; data curation: S.K., D.S.V., P.D. and A.S.; writing – original draft preparation: S.K., D.S.V., P.D. and A.S.; writing – review and editing: E.K., W.S. and Ł.W.; visualisation: S.K., D.S.V., P.D.; supervision: S.K., D.S.V., P.D. and A.S.; project administration S.K., D.S.V., P.D. and A.S.; funding acquisition: S.K., D.S.V., P.D. and A.S.

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ROZWÓJ ZAAWANSOWANYCH TECHNOLOGII PANELI FOTOWOLTAICZNYCH W BUDYNKACH – PRZEGLĄD

STRESZCZENIE

W ostatnich latach globalnie obserwuje się dynamiczny wzrost wykorzystywania energii odnawialnej. Indie również rozwijają się jako światowy lider w produkcji tego typu energii. W ciągu ostatnich kilkudziesięciu lat energia słoneczna nabrała ogromnego znaczenia jako źródło tzw. zielonej energii. Jej wykorzystanie wzrosło, w miarę jak coraz więcej właścicieli domów, przedsiębiorstw i jednostek przemysłowych decyduje się na korzystanie z tej proekologicznej formy energii. Panele fotowoltaiczne na budynkach komercyjnych pozyskują czystą energię odnawialną ze słońca i przekształcają ją w energię elektryczną, która jest wykorzystywana do zasilania urządzeń elektrycznych. Panele fotowoltaiczne składają się z wielu oddzielnych ogniw słonecznych złożonych z warstw krzemu, fosforu i boru, ułożonych w siatkę. W artykule omówiono postępy w technologii paneli fotowoltaicznych przeznaczonych do montażu na budynkach mieszkalnych, komercyjnych i przemysłowych.

Słowa kluczowe: panele fotowoltaiczne, budynki pasywne, zielona energia, rozwój zrównoważony, źródła odnawialne

THE CYCLICAL NATURE OF DUALISTIC TRENDS IN URBAN DESIGN. HISTORICAL ANALYSIS OF THE CREATIVE ATTITUDES OF SELECTED MASTERS OVER THE CENTURIES

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ABSTRACT

In this article, the authors raise issues of dualistic solutions in urban design and city development. It should be noted at the outset that the very concept of duality is not obvious and is inherently ambiguous. The numerous definitions that exist are very general. We can distinguish several disciplines and scientific areas where the concept of dualism occurs or can appear. At the same time, the definition of each of these phenomena will be different, depending on the area in which it occurs. Hence, the authors have made a far-reaching reduction in the types of dualisms, narrowing the area of research to the creative attitudes of urban planners, philosophers of space, artists, and architects in historical terms. The aim of the search for dual features in spatial forms is to find the key to a better understanding of the laws governing urban planning and urbanisation processes. Verification of opposites and dual characteristics takes place on three levels: community, form, and function. The urban conditions that occur contribute to the creation of new qualities and new spatial forms, which help redefine the city and its development. The paper is based on the thesis that dualism is a permanent feature of spatial solutions (a recurring feature) across the spectrum of history.

Keywords: urban space, spatial dualism, urban planning, history of urban structures, dichotomy in urban space

INTRODUCTION

In terms of an urban-spatial issue, it should be noted that dual divisions have accompanied both the city and its architecture since their beginnings. When thinking of a city, it is important to remember that it is a conglomerate of many different activities, connected by many definitions. There is no single definition of a city. Aristotle proclaimed that ‘a city is people’, not just the walls, buildings, or infrastructure.

At the dawn of the modern city, the minimalism of the functionalists was a proclamation of a new vision of the city – a vision, however, that was subjective, narrowing the multifaceted, interactive nature that is the city. In response to the famous words of the functionalists related to the miniaturisation of housing needs, but also urban needs more broadly that ‘less is more’ (proclaimed by Mies van der Rohe), more than 30 years later, Robert Venturi retorted from a postmodern position that ‘less is boring’ (Venturi, 1966), and

architecture – the shaping of urban space – should result from contrast and the search for duality, for example, the interior and the exterior.

On the other hand, according to sociologists of space, such as Alexander Wallis and Florian Znaniecki, a city is a cultural area. It is a particular form of space ‘which is the subject of a long-term and intense interaction between the material, aesthetic, and symbolic values contained in it and the urban community’ (Wallis, 1979, p. 17).

In his book, sociologist Richard Sennett points out another dichotomy – rurality and urbanity (Sennett & Konikowska, 1996). Referring to the territorial structure, Sennett believed that: ‘a city is a human settlement in which strangers are likely to meet [...]. In such an assemblage of strangers who come into daily contact with each other, there is an audience problem similar to that faced by an actor in the theatre’ (Sennett & Jankowska, 2009, pp. 72–73). Thus, referring to Aristotle, who wrote that: ‘a city is made up of people of different kinds; people alike cannot make a city’ (after Sennett & Konikowska, 1996, p. 46).

Also, Christian Norberg-Schulz, in his considerations, develops the theory of architectural space and the theory of existential space (Norberg-Schulz, 1971), describing the characteristics of space on the basis of dualism. The same is true of Cartesian dualism. We should not forget about the most important statement that space should be understood dualistically, as Descartes wrote. His *res extensa* and *res cogitans* presuppose the existence of two independent primeval elements: immaterial and material substance, to be developed by subsequent generations of philosophers. According to 20th-century considerations of space and place: ‘Extensibility along, across, and into constitutes the nature of bodily substance; and thinking constitutes the nature of thinking substance. [...] Thus, for example, nowhere else but in an extensible thing can shape be grasped, and motion only in extensible space; similarly, nowhere can imagination or feeling or will be grasped but in a thinking thing. But conversely, one can grasp extensibility without shape or without motion, and thinking without imagination or without feeling, and the same is true of the other things’ (Descartes, 1685).

Urban-spatial issues that have been discussed largely concern the city. In his reflections on the essence of architecture and urbanism, which bind the concept of systemic order, Immanuel Kant emphasises the division that occurs between the concepts of architecture and urbanism. By introducing, as Kazimir Severinovich Malevich later did, but in a slightly different context, the concept of architectonics, he gives the notion of city architecture a new dimension to the relations that arise between the idea of architectonics of the mind and the concept of architectural space, the existential space of its life (Kant, 1957, p. 577).

THE MAIN GOAL OF THE RESEARCH

The purpose of this article is to point out the characteristics of dualisms in urban space among the many theories and artists representing them. It is not a matter of categorising the concept in terms of space and urbanism, as it is expressed in the title, but far more broadly, considering certain borrowings, searching for common elements with modernity, beyond historical divisions. The narrative adopts a chronological approach with a breakdown of the typologies of dual divisions occurring in each historical period.

DUALISMS. THE PROBLEM OF DEFINING THE PHENOMENON

The fundamental problem in addressing the subject at hand is the difficulty of defining the phrase itself – dualism. The word itself has a Latin root – dualism – which translates as dual or two-fold, which should also be interpreted as heterogeneous, incompatible with each other as a whole. This is a very broad, multidisciplinary expression and phenomenon, present in the literature of many areas of science.

Dualism as a term – an attempt at definition and redefinition

The basic division of the expression that is dualism is based on its relationship to man as an entity. In general, we can distinguish two trends: dualism of man and dualism of man's environment.

All philosophical ideas (and religious systems) from Antiquity to the present operate within the framework of the dualism of man.

These will be the dualisms of Plato (mental and sensory cognition), Aristotle (every human being consists of matter and form), René Descartes (soul and body are independent entities), Immanuel Kant (division between empirical and transcendental cognition), Martin Heidegger (a human being is distinct from all other entities), Max Scheller (the presence of the world conditions the existence of the human person), Roman Ingarden (the division between the 'me' of the object and the 'me' of the human being), Kitarō Nishida (dualism in Zen philosophy), radical dualism (the concept of a 'good' God and an 'evil' God – Manichaeism), or Friedrich Nietzsche (the thesis that the world is the will to power).

Within the dualism of man's environment, several dualisms can be identified concerning various spheres of human life. These will be dualisms such as: political dualism (two conflicting goals of life – common good and individual good), economic dualism (two economic zones of Europe in the 16th–17th centuries), spatial dualism (space is not homogeneous), or corpuscular-wave dualism (diffraction and interference).

Dualism in urban planning – definition – exclusions adopted by the authors

When considering the spatial (or urban) dualism mentioned in the subsection 'Dualism as a term – an attempt at definition and redefinition', which will be the basis of this discussion, we need to realise its further internal divisions. Thus, the simplest to distinguish and confront in the space of cities is the division (1) into old and new districts (Carcassonne). Such a division applies to the overwhelming number of historical cities that developed over hundreds and sometimes thousands of years. Today, for the most part, they are capitals of European cities, important tourist destinations, significant commercial centres, or ports.

Thinking about dualisms in space, it is impossible not to also notice the numerous groups of dual cities, i.e. cities divided by a boundary line (2), because of political and treaty solutions. Many such cities have appeared, especially in Europe in the 20th century. These include, for example, such city pairs as Guben/Gubin, Zgorzelec/Görlitz, Frankfurt/Slubice, Kostrzyn/Küstrin-Kietz, Cieszyn/Ceský Těšín, Komarno/Komarom, Gorizia/Nova Gorica, Nicosia/Lefkosia and many others.

When considering dualisms in urbanism, one should also add the elements of the natural environment (3) resulting from the choice of location for the construction of cities and the unique physiography of the terrain associated with this place (Sorrento), or the phenomena of tides (Mont Saint-Michel). It is also possible to distinguish cities built in characteristic bends of rivers (Kamenets Podolsky). Further, one can mention cities separated by a river, and these, after all, are numerous, or, finally, cities on islands or lagoons.

The authors of this article considered that all three above-mentioned groups (1, 2, 3), are dichotomies resulting from divisions between historical and modern districts within a single urban organism, as well as political and treaty solutions, or divisions resulting from natural conditions and should be excluded from the research on the issue at hand, as they are devoid of intended human creation, i.e., compositional value consciously proposed by the designer-creator.

Dualism in urbanism – a proposal for a narrower definition

The authors of this article propose a consciously and deliberately narrowing definition of the phenomenon of dualism, as an urban-spatial solution, reduced to two main currents. Both currents are related to the activity of man as an artist, the creator of urbanism, from a historical perspective. The first unites outstanding figures from the world of urban planning theory, philosophers of art, and philosophers of space, while the second current unites outstanding figures from the world of executive practice, mainly urban planners and architects.

RESEARCH MATERIALS AND METHODS

Current state of research – discussion of the main works of literature on the subject

Dual issues have been present in works by many authors from different historical periods (Fig. 1). In the matter in question, we distinguish four main currents, which include the works and figures highlighted below:

1. Theoreticians and practitioners of urban planning and architecture: Vitruvius, Theo van Doesburg, Mies van der Rohe, Frank Lloyd Wright, and Le Corbusier.
2. Sociologists and philosophers of space: Martin Heidegger, Edward Hall, Kevin Lynch, Florian Znaniecki, and Janet Abu-Lughod.
3. The utopians of the social idea, most importantly: Thomas More, Charles Fourier, Robert Owen, and Jean-Baptiste André Godin.
4. The final category includes political scientists and historians who describe the socio-political relations and issues in the economy and geography of cities of various historical periods. The following authors and their works should be mentioned: Friedrich Engels, David Harvey, and Jane Jacobs.

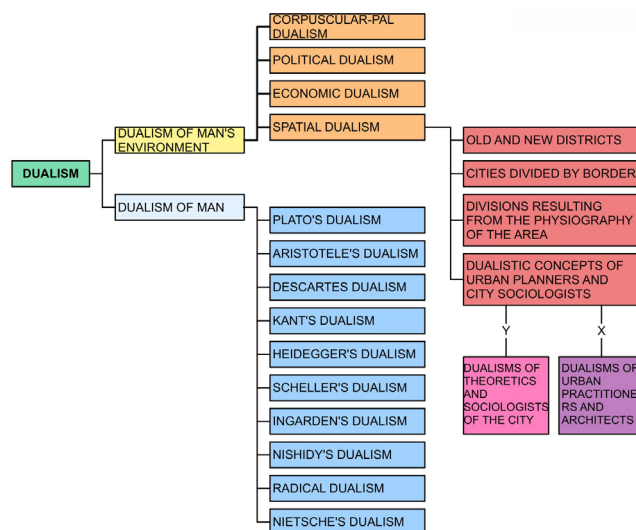


Fig. 1. Dualisms – different forms and divisions, basic categorisation

Source: own work.

Purpose of the paper and main research questions

Dualisms in built-up space (urban-architectural space) are not a homogeneous phenomenon. They are often the result of the coincidence of multi-criteria factors arising from the realities of time and place. In the rich literature on the subject, there is no uniform formula for categorising this phenomenon. The purpose of the paper is indeed to introduce such a categorisation and to identify the relationships and areas of influence and interaction between different forms of spatial dualisms. The main research questions formulated by the authors of this paper focus on two issues. The first is the following question: Is a coherent categorisation of the phenomenon in question possible, and if so, according to what means is it possible to build it? The second issue addressed in the paper is the validity of the historical perspective for demonstrating the aforementioned relationships between the proposed categories.

Form of the paper

The text presented is an overview paper. The authors have identified several dual phenomena from a time perspective, from Antiquity to the present. The entire historical period has been divided into seven conventional stages, which have their counterparts in the subsequent historical periods and styles, such as Antiquity, Middle Ages, Renaissance, and Baroque, up to the present. In each of these seven stages, the team of authors arbitrarily selected the most characteristic examples of spatial dualisms, from two to four cases. These are described in the various subsections of this paper. The conclusions section starts with information presented in one table and a diagram.

Work methods

The main work methods are qualitative methods and a mixed–triangulation method. More specifically, these will be case studies, the method of analysis and logical construction, the method of literature critique, the method of observation, the deductive method, the comparative method, and the method of synthesis.

THE SEVEN STAGES OF DUALISMS IN SPACE-TIME DISCOURSE

Pragmatism of functionality

Dualism is inherent in our world and has been an interesting issue addressed by many philosophers and thinkers since ancient times.

The Greeks refer to it as *τόπος* (place), *χώρα* (space) and *κενόν* (vacuum). ‘Aristotelian space’ (Jammer, 1957, p. 20, after Heller, 1993), specified the definition of place as the location of a body in space – ‘the immediate and immovable boundary of the surrounding body’ (Reale, 1990, p. 297), thus providing the concept of finite space.

Rational thinking is especially close to the philosophy of ancient writers on space theory. Modern generations (Y and Z) are characterised by pragmatism in making and implementing life or career decisions. This fact is emphasised by many contemporary sociologists (Berg, 2006, after Hildebrandt-Wypych, 2009). A trans-historical axis of similarities is thus emerging before our eyes. Today’s youngest adults and ancient writers manifest a similar way of thinking, but a very different value system. It is worth noting a couple of dual elements expressing this pragmatism in ancient space theory. Marcus Vitruvius believed that a city is simply one big house. We build it just like any other house, with the difference that a city is much more complicated and extensive. And here, Vitruvius turned out to be much more conservative than the father of world urbanism, Hippodamus of Miletus, who lived a few hundred years earlier. For him, urbanism (the science of building cities) was not the same as architecture (the art of building cubic structures). It is generally believed that Vitruvius must have been familiar with at least parts of *Treatise on the Formation of the Polis* by Hippodamus of Miletus, such as those preserved in the writings of his friend Aristotle, since his work *Ten Books on Architecture* contains several very similar elements. Both stated that the hierarchical nature of space is the main factor in building its harmony and the designer’s composition - the only one legible, in their opinion, to any user of space. On the other hand, the pragmatism of the Romans was reflected in Vitruvius’ idea to depart from the modularism of Hippodamus, especially when it came to the shape and functionality of the forum – the ancient Greek agora. It was no longer a 1 : 1 ratio of the square’s walls but evolved to 1 : 1.5 so that more commercial functions such as basilicas, *lararia*, and *macella* could utilise it. The Romans also departed from Greek modularism in many other areas of space shaping by establishing, for example, the archivolt.

The contrast between Roman and Greek divisions is shown by the Hippodamian city divided into districts, each with a local centre, as is the case, for example, in the city of Millet designed by Hippodamos. Each district has its own modular grid, the size of which reflects the social and professional status of the residents.

The districts took advantage of the different physiography of the area, which was followed by divisions, an element completely absent in Vitruvius.

Vitruvius's dualism, in turn, was revealed in the optics of a bipolar downtown. These two poles were centred around ensembles of different urban functions. The first pole combined administrative and commercial functions (forum, treasury, basilica prison, temple of Mercury). The second pole contained functions related to the ambitions and needs of shaping a physically and intellectually healthy lifestyle of the residents (theatre, circus, gymnasium, temple of Hercules).

Anthropomorphism – the language of humanism

Along with the humanism of the Renaissance and the new interest in man, there was also a new vision of the space surrounding us at the scale of the city, province, or region. Alongside the search for regularity of form (the path to simplicity and purity of layout), there was, at the same time, an affirmation of the proportions and symmetry of the human body as perfect and the ascribing of layout features and values to them (Alexander, 1973, p. 10).

This anthropomorphism appeared mainly symbolically, but also sometimes broadly, more literally, eventually reaching – for some theorists – even for physiological-anatomical comparisons.

The creators of this period used the importance of similarities even where, rationally, it may have been difficult to imagine them. Underlying this anthropomorphism was a new approach to understanding the three-dimensional world, where complementarity and hierarchy successively reduced the elements of repetition.

For example, it is necessary to point out the distinctive double voice of Francesco di Giorgio Martini and Vincenzo Scamozzi. Martini assumed an anthropomorphic functional theory of the city, which derives from Vitruvius's golden ratio, where the human figure is contained in the plan of a circle – the ideal figure. However, he is not concerned with formal relationships and references to individual parts of the human body, but with symbolic relationships. In the described metaphor, the head of the city is the castle, the place of the belly is the central square, and the cathedral is the heart. The limbs act as defence towers. The analogies are all too obvious; the castle constitutes the existence and secures the possibility of development of the city, and the heart ensures blood circulation, i.e. the correct level of social relations, and the other organs are necessary not for the existence and functioning of the urban organism, but for competing with other cities. Similarly, as well as the bipolarity resulting from anthropomorphism, the complementarity of the various functions of the human body (limbs, organs of sight and hearing), the city also contains the principle of subsidiarity. Giorgio Martini is thus the forerunner of complementarianism in the concept of the city (Fig. 2).

Vincenzo Scamozzi, on the other hand, looking for dual elements, notices the fundamental changes in the structure of cities from ancient times to his time (late 16th century and early 17th century). His theory of the anthropomorphic construction of the city differs significantly from Martini's concept (Zarębska, 1970, p. 150). Yet another aspect of his anthropomorphic treatment of architecture is found in his comparisons of city streets to the veins and arteries of the body, whose rank and importance are strictly defined and differentiated. The buildings, individual palaces and squares of the city correspond to different organs, and their shape, size, and location depend on their role.

Anthropomorphism in city planning was also present in Poland, in the only fully realised European example of the ideal city of the Renaissance era – Zamość. It was the capital of the Zamoyski magnate family. Zamość was designed by the prominent Italian architect Bernardo Morando. Construction spanned the years 1600–1651. The idea was to combine two regular figures – a rectangle and a regular hexagon – into a single whole. The project also considered the improvement of security conditions, adding a bastion layout to the original design, based on the natural floodplains of the Łabuńka river. Anthropomorphic references can easily be seen in the structure of the interconnected figures, where the centre of the rectangle is the Zamoyski Palace – the most important point and the head of the entire layout.

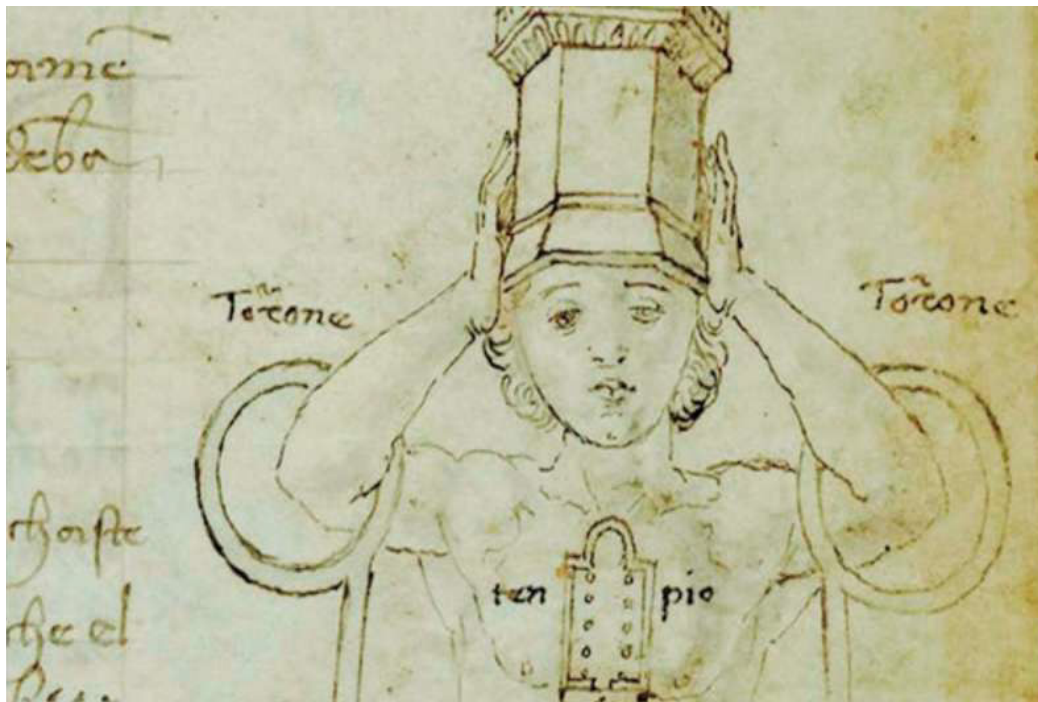


Fig. 2. Fortified Man – a 15th-century city concept by Francesco di Giorgio Martini

Source: di Giorgio Martini (c. 1470), © Turin Biblioteca Reale.

Below the palace are the cathedral (collegiate) and the academy – two lungs of spiritual and intellectual heritage – *fides et ratio*. The central part of the hexagon is occupied by the main city square with the dominant city hall, symbolising the heart, next to which is the market – a melting pot of urban activity, reminiscent of a nutritional system.

Between geometry and symmetry – in search of the perfect form

The regular form of a circle or regular polygon was originally dictated for defensive purposes in the ancient period. Although the first treatises of modern authors still raised the value of the regularity of the layout for the defence of the city, especially to support its bastion solutions, nevertheless, there were more and more attempts to develop an ideal city layout, based solely on the search for the perfect form. The main representatives of this trend in the Baroque and Enlightenment periods were representatives of radically different visions of the functioning of man in space.

On the one hand, there were the creators, working in the service of French absolutism (here specifically Cardinal Richelieu), such as Jaques Lemercier – royal architect since 1615, creator of the Château de Richelieu and the Palais-Royal. Widely considered one of the finest examples of a Baroque city, Richelieu's city was based on an orthogonal structure, where a centrally derived axis connected two twin squares. The symmetrical solutions emphasised axuality, which in turn emphasised the hierarchical nature of space, as well as power.

Much further from absolutism, we find two later figures – Étienne-Louis Boullée and Claude-Nicolas Ledoux. The former, active in the Classical period and fascinated by the first successes of mankind associated with the Industrial Revolution, believed that architecture must face the challenges of the new era. It was his universalist belief in the capabilities of inventors that drove his search for the perfect form and physical realisation. It is in this spirit that he designed Newton's mausoleum-cenotaph – a sphere-shaped object

of monstrous size and scale. This physical form never came into existence; it remained a utopia, but it had a great influence on later generations and artists, especially those of the late 19th century and early 20th century.

While Boullée was part of the universalist trend, the victory of man over nature (the invention of the steam engine, the development of the railroad), Ledoux, working at a similar time, was looking not so much for the perfect form to emphasise the universalism of the message, a tribute paid to humanity, but in general to reconstruct society according to a new formula, not based on the traditional values of the family or the Christian values dominant in Europe at the time.

À rebours city-states – utopians of the social idea

The crisis of urban overcrowding, triggered by the Industrial Revolution, led to the development of numerous utopias, bringing hope for a rearrangement of social relations and, in this context, also functional-spatial relations. In response to the overcrowding of large cities and the large scale of social pathology, the spatial theorists of the time brought to life numerous concepts of new settlement forms, whose main goal was to generate a new social order. Such a form of morality play on the life of a new, ideal republic-utopia is known from the novels of Thomas More. He is regarded as the first socialist since his vision contains a profound egalitarianism at its core. He is the first and one of the few forerunners of the Just City, a concept developed in modern times by Susan Fainstein. In his understanding, the state should consist of cities providing identical opportunities for development, which, as we know, is not a simple thing, if at all feasible. Therefore, his republic consisted of cities identical in size (number of inhabitants), as well as in functional and spatial structure. The urban layout was based on a regular quadrangle with an orthogonal arrangement of streets and building quarters (More, 1912, pp. 87–116). The quarters were enclosures, inside of which there were gardens. In the city-state of Utopia, there was no cash circulation, and the most expensive plots of land in the city were intended for holiday celebration houses. Thus, in place of the worship of money, we see here an affirmation of the community, the family, as well as the individual resident. It is also an affirmation of the city, one of the strongest in the entire history of urbanism. One example is the strictly recorded number of cities in Utopia – 54. The obligation to maintain this number was more important to him than territorial expansion – colonial acquisitions, which he accepted without counting their costs. The only explanation is the symbolism of the numbers he used. We have families of 24 people here, and cities of 144,000 inhabitants (6,000 families). These numbers, it seems, refer more to salvation history, the interpretation of the meaning of numbers in the Old Testament and the Apocalypse of St. John to urban planning.

Thomas More paved the way for subsequent treatises on the ideal city-state in the era of rival imperial states when these solutions were already an anachronism. Due to the presence of numerous dual solutions, it is impossible to omit Charles Fourier's *Phalanstery* and Robert Owen's *New Harmony*. Fourier, like Ledoux, attempted to create a new social structure based on his own functional-spatial formula of novel settlement units. In Fourier's case, it was the phalanstery – a people's palace inspired by Baroque imperial residences. Unlike More, Fourier based his settlement structure on the cohabitation of many families and single people with extremely different personalities and temperaments. Within the framework of the phalanstery, he favoured social selection devoid of the existing hierarchy and traditions and was to be based without priority for families. The strongest dual context here concerned the difference between the phalanx and the phalanstery. The phalanx, or small commune, resembling the size of modern French communes, was based on agricultural production on 20 km² of farmland, whereas the phalanstery spire was based on a magnate or royal residence. Fourier's experiment was never realised, but years later, in the second half of the 19th century, Fourier's inspiration found an imitator – Jean-Baptiste André Godin. His *familistère* concept – expanded to include a plant for metallurgy and iron products – operated for several decades until the outbreak of World War II. Godin's concept did not include social experiments and, unlike the phalanstery, was based entirely on workers functioning within a traditional family.

Robert Owen was active, like Godin, a little later than Fourier, in the 19th century, and was one of the few significant polemicists of Malthus' theory, which claimed that the rate of world population growth was outpacing the capacity to produce the food necessary to sustain it. The early 19th century was a time when Europe, devastated by the Napoleonic wars, was experiencing severe food shortages. In conclusion, the most suitable settlement unit, in Owen's opinion, was to be an industrial-agricultural settlement, producing food and food products. Many such enterprises would certainly reduce food prices and allow masses of unemployed people doomed to poverty to move out of the industrial cities. The production base for each such settlement was to be 480 ha of land, while residents would live in settlements in the form of a vast parallelogram, made up of terraced housing segments of two to four storeys. Many of these utopian solutions have guided the real transformation of the European creative city from the 18th century through to the 20th century (Florida, 2019, pp. 28–32).

Masters see dually

‘Space-time launched the modern movement in architecture’
(Giedion, 1967)

In the program of Theo van Doesburg, one of the key representatives of the De Stijl group, we find a description of the impression of the idea of space as an entity with four or more dimensions. He embodies the central problem of visual arts when he points out: ‘The new architecture considers not only space, but also the magnitude of time. Through the unity of space and time, the architectural exterior will acquire a new and completely plastic aspect [...] The new architecture is anticubic – it does not attempt to fit all functional spatial cells into a closed cube, but designs functional spatial ceilings (as well as overhanging surfaces, balconies, etc.) from the centre of the cube outward.’ (Gropius, 1971, p. 78). Doesburg's approach to redefining the concept of architecture was based precisely on dualism, concerning form without concept, a substance without shape, or the simultaneity of interior and exterior.

Three concepts of space competed within Bauhaus: those of Walter Gropius, Mies van der Rohe, and Laszlo Moholy-Nagy (Pevsner, 1936, pp. 142, 146–149). According to the first of the masters, it is the category of understanding the surrounding world through the prism of the soul, mind, and senses, which, according to Mies van der Rohe, defines most perfectly the return and ennoblement of craftsmanship as a new renaissance in art and also in architecture, where the material became a new model, a new body, and, thanks to the ‘human breath’ – perfect. Moholy-Nagy went even further by getting very close to the Suprematists when he claimed that the concept of space also included architecture and the relationship between the position of bodies. In other words, with each of them, there was an additional synonym, attribute, or context of space which redefined it. These attributes, inherently complementary, paradoxically created a bipolarity of the phenomenon (Bahnam, 1960, p. 189).

We cannot forget to mention the two prominent figures of modernism, Frank Lloyd Wright and Le Corbusier, in this comparison, with their wildly different perceptions of dualisms in spatial contexts. Le Corbusier proclaimed the ‘city in the park’ idea of a natural rapprochement – bordering on an impressive rivalry – between the forces of nature and the power of human thought (Jencks, 1973b, pp. 114–118). He believed that man would meet this rivalry with the novelty of structures, the possibilities of materials, and the aesthetics of glass, steel, and concrete (Banham, 1960, pp. 247, 251–252). By design, he wanted an anonymous city where everyone benefits from everything, where people live like a fraternity, working for the common good, while Wright built his Broadacre City with the idea of a society composed of neighbourhoods based on property, similar to the one that shaped the pioneers, the conquerors of the West. Wright's city is immersed in the greenery of individual plots the size of an acre, whereas in Le Corbusier's case, there are no private plots at all (the modern city and the radiant city). The dichotomy also grew out of Le Corbusier's attempt to free man from the excess of responsibilities involved in handling space. He believed that the pace of life compelled

minimalism in the realm of both functional and surface areas of living spaces. Wright, on the other hand, saw the future not so much in minimalism, but in new infrastructural solutions, such as new forms of public transportation like aerial cabs (Jencks, 1973a, pp. 368–372).

Space and location in the discourse of philosophers of space

Among philosophers of space, especially modern philosophers, there was a belief in a dual understanding of it. It was, on the one hand, three-dimensional Euclidean space understood as a place occupied by material bodies, in which emptiness is possible and necessary. On the other hand, it was space as a mentally visited place.

The late 19th century and early 20th century initiated wide-ranging discussions about space and place. At that time, a new field of phenomenology emerged, which began to emphasise the importance of space in terms of the place ‘between things’ (in Husserl’s case). Heidegger develops this concept and speaks of *Räume*. Here, for the first time, the phenomenon of tangibility appears and takes on a new face, a new expression which is room and space (from the German *Räume*): ‘The spaces (*Räume*) in which we pass every day are arranged (*eingerräumt*) by places (*orte*), the essence of which is grounded in things like buildings’ (Heidegger, 1994).

Heidegger’s dual views of interior and exterior, including his most important work (Heidegger, 1994), also contributed to the development of the concept of space in an architectural context, for he argued that ‘the relationship of man to place and through places to spaces consists in inhabitation’ (Heidegger, 1994, p. 333). A continuation of this thought can be found in German philosopher Otto Friedrich Bollnow, in whom the concept of *Geborgenheit* appears, and in Edward Hall, the concept of *Eigenraum*, meaning territoriality. Bollnow’s existential considerations are based on the relationship between man and space. ‘Man lives (in a certain place that belongs to him) in space’ (Bollnow, 1963, pp. 499–514), developing the concept of space by referring to the main dualism – interior and exterior.

Hall, on the other hand, writing about space, uses the term *Eigenraum* (territoriality). For him, it is associated with a certain framework – ‘an individual claims a certain area, defends it from the representatives of his species [...] creates a certain framework in which everything is done, and these are places for learning, places for playing, safe hiding places’ (Hall, 1990, *Note 5*). At the same time, Hall believes that humans live simultaneously in different spaces, which leads to experiencing different imaginations of the same space, and each imagination is based on a different sense.

Kevin Lynch, on the other hand, focuses on the experience that arises from the relationship between an inhabitant and a specific area in which he moves – ‘this image is a product of immediate sensations and memory of past experiences’ (Norberg-Schulz, 1971, p. 15). On this basis, Lynch created an imaginary map based on the division of the environment into five elements such as landmarks, nodes, paths, edges, and regions. ‘The world can be organised around a set of focal points, broken into named regions, or connected by remembered paths.’ (Lynch, 1960, p. 7).

The renowned city sociologist Florian Znaniecki talks about space conditioned by cultural aspects of a symbolic nature. These spaces, which Znaniecki refers to as ‘spatial values’, are diverse ‘they are, for example, occupied or empty places, spacious or cramped interiors and, in contrast, “exteriors” – residences, neighbourhoods, centres, borders, measured areas, non-measurable spaces, etc. [own transl.]’ (Znaniecki, 1938, p. 89). Each is a component of some non-spatial system of values, in relation to which it has a specific content and meaning. It can be a religious, aesthetic, technical and creative, economic, or social system. Moreover, the space experienced by humans is diverse and changeable.

Ewa Rewers introduces a new conceptualisation of urban issues, and sees the city as a place of traces and voids ‘the hermeneutics of the trace can only be thought of if we prove that beyond language, however, lies the area of the unspeakable and that it is the traces we leave behind and found by others that tip the suspicion of its existence [own transl.]’ (Rewers, 2005, p. 28).

In the context of dualisms, they are considered by many theorists to be naturally coexistent. Norberg-Schulz describes them in an existential context – ‘the notions of proximity, centrality and closure thus work together to create a more concrete concept of being, a concept of place – and place consists of the basic elements of existential space.’ (Norberg-Schulz, 1971, p. 91). Thus, he refers to the theories of Edward Hall, Otto Friedrich Bollnow, and the works of Dagoberto Frey, Rudolf Schwarz, Jean Piaget, and Kevin Lynch.

Dualisms in the scale of the urban interior

Space in urbanism is also a simple urban interior, such as a square or street with a specific landscape context surrounding natural or built objects. Paradoxically, it is the dualisms used here that raise the dynamics of the message, and make the obtained dimension of the cultural landscape of the interior more expressive, rich, more easily remembered, and sometimes shocking. Many artists use this effect when designing spaces for their projects of commemorative places and ensembles. Artistic street design concepts and street art projects, as well as other artistic events and street theatres, function based on consciously introduced dualisms (Fig. 3).

Both Renzo Piano and Richard Rogers built according to this convention, erecting the famous Beaubourg in Paris. Another example is Charles Moore’s Piazza d’Italia (Jencks, 2011, pp. 56–58). Both buildings were constructed in the mid-1970s (1976) and have a narrative of contrast. Following a wave of social protests, France, under Prime Minister Georges Pompidou, needed a building that would express the power of France at the time in a peaceful or even pacifist manner. The chosen team accomplished this task perfectly. The result was a building and plaza in the centre of Paris (dedicated to Pompidou) the size of two quarters of the historical development. However, it does not resemble, in any way, the Paris of Haussmann’s renovation. It definitely departs from the convention of the development structure perpetuated for generations, but it is also not a typical example of modernism encapsulated in Le Corbusier’s five theses. Perhaps this is because it was created after 1972 and the demolition of the Pruitt-Igoe estate in St. Louis, which was the end of dogmatic modernism (Jencks, 2011, p. 27).

Following their own path, the authors here used a game of contrasts, deliberately defining a series of dualisms within the designed ensemble as a new definition of the classical principle of compositional hierarchisation of space. Thus, we have two connected quarters of a historical development. However, they are not constructed in the traditional way. Half of them form a building, while the other half is a square preceding the building, filled with cobblestones and numerous tubes resembling powerful air intakes for internal ventilation. The museum itself (Centre Georges Pompidou) is the first building in history without a façade.

A similar game of dualisms to achieve essentially similar goals was proposed by Charles Moore in the realisation of Piazza d’Italia. Here, the role of the historical structure is played by the modern downtown of New Orleans, built in a modernist style, arbitrarily devoid of detail, with pure form. Here, where we would expect another ‘success’ of pure form, the author surprises us with a postmodern game of irony, embedded in the deep historicism of European architecture, specifically the architecture of Roman antiquity. This urban public square announces the American Italian Cultural Center (AICC), which is located there. A game of contrasts emerges, which includes not only the powerful difference in scale of the adjacent buildings, but also in colour and form. Moore uses bright sepia and ochre, showing the rhythm of numerous arcades with irreverently modified architraves, an altered role of metopes and triglyphs, and romantic repetitions of archivolt. The result is one of the most perfect realisations of the ideological program of postmodernism.

The appeal to dualism need not be as spectacular as in the two examples above. It can be much more modest, for example, at Franklin Court in Philadelphia. It is located within Independence National Historical Park in Pennsylvania. The site where Benjamin Franklin’s home once stood is marked only by the outline of a metal profile. In this way, no interpretation is imposed on the user of the space. The concept allows the visitor’s full attention to be shifted to Independence Hall, where the Declaration of Independence was adopted in the late 18th century.

	Start dates	End dates	A historical figure or city or place as the subject of the formation of the dualistic concept	Thematic group considering historical succession
1	510 pne	443 pne	Hippodamos z Miletu	Pragmatism of functionality
2	76 pne(?)	14 ne(?)	Marcus Vitruvius Pollio	
3	1439	1502	Francesco di Giorgio Martini	Anthropomorphism of the Renaissance
4	1548	1616	Vincenzo Scamozzi	
5	1540	1600	Bernardo Morando	
6	1585	1654	Jacques Lemerrier	Between geometry and symmetry
7	1728	1799	Étienne-Louis Boullée	
8	1736	1806	Claude-Nicolas Ledoux	
9	1478	1535	Thomas More	Utopians of the social idea
10	1772	1837	Charles Fourier	
11	1771	1858	Robert Owen	
12	1817	1888	Jean-Baptiste André Godin	
13	1883	1931	Theo van Doesburg	The masters see dually
14	1867	1959	Frank Lloyd Wright	
15	1887	1965	Le Corbusier	
16	1886	1969	Ludwig Mies Van Der Rohe	
17	1882	1958	Florian Znaniecki	Space in the discourse of philosophers
18	1889	1976	Martin Heidegger	
19	1926	2000	Christian Norberg-Schulz	
20	1914	2009	Edward Hall	
21	1972	Centre Pompidou	Renzo Piano,	Dualisms of the urban interior
22	1977		Richard Rogers	
23	1978	Piazza d'Italia	Charles Moore	
24	1988	Falkestrasse	Coop & Himmelblau	
25	1995	Reichstag	Christo (Wladimirow Jawaszew)	

Fig. 3. Historical figures and the subjects of the formation of the dualistic concept

Source: own work.

In almost the same period, there were artists operating with large spatial forms as a means of artistic expression. They based their work precisely on the construction of impressionistic spatial dualisms. The most prominent among them was Vladimirov Yavashev, who used the pseudonym Christo. In his most famous works, we can notice characteristic large-scale, tight, almost ‘postal’ packaging of cubic structures, which are carriers of historical tradition. The idea was to use the simplest, neutral texture of the material from which the packaging was made. This material did not carry any meaningful content, exactly as is the case with postal packages. In this way, Christo achieved the impression of packing a spatial object before travelling, shipping, or selling it. This effect illusorily deprived the place of the permanent location of structures and buildings with a significant role in European history, such as the Roman aqueducts, the Arc de Triomphe in Paris and the Reichstag building in Berlin. In the case of the latter, the emotional message of stopping in time was clearly related to the return of the parliamentary function of the building after German reunification. At the same time, it was meant to represent a repudiation of the grim history associated with the building during the Third Reich. Christo’s work was intended to provoke reflection on the values and material culture of cities, and on the structures that constitute Europe’s historical heritage (Fig. 4).



Fig. 4. President of the Bundestag, Prof. Dr. Norbert Lammert, with Christo on Wednesday, 25 November 2015; Vladimirov Yavashev's (aka Christo's) Wrapped Reichstag

Source: © DBT/Melde 2015.

Alienation in relation to historical context was, one might say, quite fashionable in the late 1960s and early 1970s. All the projects of the ARCHIGRAM group, for example, appeared on this basis (Sadler, 2005, p. 47). Other examples of projects on the scale of urban interiors using dual solutions to enhance their impact and impression layer can also be observed. The first departure from the traditionally understood interior towards artistic street design concepts was the famous postmodern remodelling on Falkenstrasse by the Coop Himmelb(l)au group in a 1983 project in Vienna (Jencks & Kropf, 2006, pp. 286–287). This created a special place, living with its own memory on the mental maps of every user of the space. Here, the contrast was not only intentional, but even constituted a new spatial expression as an immanent feature of the project itself.

The same is true of street art, which enters urban spaces in neglected, featureless places, where the similarity of structures and forms does not allow a place to develop its own identity.

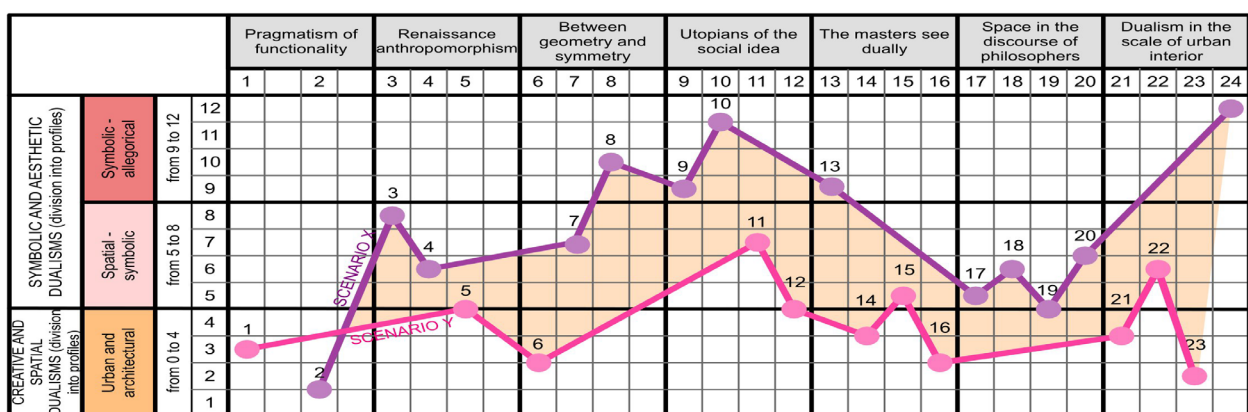
In the 21st century, we can also see a breakthrough in this regard concerning commemorative places and spaces. Here, we have several dualisms concerning both the form, opposing metaphors, the active role of the environment (The Diana, Princess of Wales Memorial Fountain by Gustafson Porter + Bowman, London, UK), and the texture of the materials used.

Almost all museums built after 2000 are based on the new role of contrasting messages, such as closures versus openings, linear or point versus area layouts (the Pentagon Memorial by Julie Beckman and Keith Kaseman, Arlington, Virginia, USA), colour contrasts (the Poppy Plaza by Marc Boutin Architectural Collaborative and Stantec Consulting, Calgary, Canada) built versus natural forms (the Memorial to Victims of Violence in Mexico by Gaeta Springall Architects, Mexico City, Mexico), regular and irregular (the Space Mirror Memorial by Holt Hinshaw Pfau Jones, Merritt Island, Florida, USA), and symmetrical and asymmetrical.

DISCUSSION

The main framework of the concept – description of the diagram

The attempt at categorisation is illustrated in detail in Figure 5. The concept adopted by the authors to organise spatial dualisms involves categorising the phenomenon described in the chapter, ‘The seven stages of dualisms in spatial-temporal discourse’, which presents a division into periods of historical narrative – according to three four-level areas. These three areas are defined according to the criteria for the dominance of creative values. The main axis separates three areas: urban-architectural dualisms, creative-rational dualisms, and symbolic-allegorical dualisms.



Explanation: Scenario Y (marked in purple) is heterogeneous by design. This scenario is dominated by creators and examples of cities with firmly established practical solutions; this scenario also includes examples of the work of outstanding practising urban planners. These are the following numerical items and creators: (1) Hippodamus of Miletus. The figures of the creators-architects representing the successive historical periods are (5) Bernardo Morando, (6) Jacques Lemercier, (11 and 12) Robert Owen and Jean-Baptiste André Godin. The modern period begins in this scenario with the great figures of modern architecture and urban planning: Frank Lloyd Wright, Le Corbusier and Ludwig Mies van der Rohe (14, 15, 16). The last period of the final decades of the 20th century ends with outstanding individuals – three creators and the architectural design teams they created. These are Renzo Piano and Richard Rogers, Charles Moore, and Coop Himmelb(l)au (21, 22, 23). Scenario X (marked in violet), on the other hand, is dominated by purely theoretical solutions, and the various cases presented there are related to famous theorists of the philosophy of space, the sociology of the city, urban planning, and architecture. Unlike Scenario Y, Scenario X is much more homogeneous and clearer. In proceeding to the numbering of the examples, it is necessary to note in the period of Antiquity (2) the figure of Marcus Vitruvius; in the period of the authors of Renaissance treaties – two figures (3, 4): Vincenzo Scamozzi and Francesco di Giorgio Martini; further, in chart positions 7, 8, 9, 10, and 13, there are such figures as Étienne-Louis Boullée, Claude-Nicolas Ledoux, Thomas More, Charles Fourier, and Theo van Doesburg. The 20th century is represented here by four philosophers of space and sociologists of the city in positions 17, 18, 19, and 20, such as Florian Znaniecki, Martin Heidegger, Christian Norberg-Schulz, and Edward Hall. The historical entity of the chart is closed by the figure of Christo (Vladimirov Yavashev) in the category of contemporary urban interior (24).

Fig. 5. The phenomenon of spatial dualisms. Historical narrative curve – by the three aggregated areas (between rationalism and symbolism)

Source: own work.

Thus, the three areas with a dominant symbolic-creative formula are included in values that are conventionally labelled as positive. When proceeding to the description of the main areas, it should be pointed out that the area containing urban and architectural solutions was placed first, with a value from 0 to +4. The second, defined on a scale of values from +5 to +8, is the area of spatial-symbolic solutions. The third, closing the value scale, between +9 and +12, is the symbolic-allegorical area, where the authors see the greatest creative charge and, at the same time, the least potential for external conditions.

Description of the diagrams. The rationale for the division into scenarios. Convergence and divergence perspective

To illustrate the phenomenon of spatial dualisms, as well as a starting material for the conclusions section, the team of authors prepared Figure 5. The authors made an arbitrary selection of examples, identified two scenarios, and characterised their course. These were Scenarios X and Y.

Confirmation of the validity of the historical approach

Both scenarios showed the validity of the historical approach since, by making the assumptions formulated above, a profound recurring cyclicity of dualistic phenomena persisting in the formation of space in Le Corbusier's urbanised environment was obtained. The phenomenon of cyclical spatial dualisms has not been described before and is a new value added by the team of authors within the scientific discipline of urban planning and architecture.

Convergence and divergence perspective

Both scenarios show far-reaching spatial correlations with each other. The lines of Scenarios X and Y form, in simplified terms, sine waves (Fig. 5).

A significant deviation of the graphs and a significant flattening of the graph line can be seen in Scenario Y. Sequence repetition occurs at an interval of about 300 years in the first phase of the graph and then accelerates and reaches an interval of only 100 years in the last – the 20th century. In addition, a mention should be made of the significant shift of the broken line of Scenario X in relation to the graphs of Scenario Y. Scenario X is significantly above the main (zero) axis of the graph and is almost entirely contained in the two highest areas – spatial-symbolic and symbolic-allegorical.

The analysis carried out in the paper allows us to conclude that it is possible to categorise the phenomenon of spatial dualisms.

CONCLUSIONS

The dualisms that are presented in this article are based on opposites that, like the mind and the body, complement each other. 'The number two, or one plus one, is complex, dual' – Mondrian writes – 'and yet it is a whole; and conversely, unity contains duality.' (Seuphor, 1956, pp. 301–310). Based on the considerations in the text, the following conclusions were drawn:

1. When analysing urban planning issues, it is necessary to look at them more broadly than just in terms of form and scale.
2. An important point is the identification of seven directional profiles in the various fields of knowledge in which duality threads are intertwined. These seven profiles intermingle and complement each other. The most important conclusion is the revealing of multiple, multi-area references and borrowings in the formation of spatial dualisms in the past and in the present.
3. The article formulates a new thesis that dualism is an immanent feature of spatial solutions across the spectrum of history. Urban planning has always fed, and continues to feed on dualisms to this day, and it takes advantage of their existence to create a new perception of space based on them, unleashing the dynamism of forms and scale.
4. The study showed that there is a noticeable cyclicity to the phenomenon of dualism in the urban-spatial area from a historical perspective. Returning to the results shown in Figure 5, it is worth noting that Scenario X contains a strong correlation with Scenario Y. The cyclicity is also evident in the graph of Scenario Y.

5. The research concerned only urban planners and architects from the cultural circle of the West, i.e. the Euro-Atlantic civilisation (optionally with an extension to Latin American culture). Therefore, the above conclusions cannot be extended to other cultures, such as Islamic culture, China or other Far Eastern cultures (Huntington, 2011, pp. 42–48). The question of the universality of urbanism was already posed by Chris Alexander (Alexander, 2015, p. 57).

THE APPLICATION VALUE OF THE RESEARCH

The presented results have a great application value. The reasonable expectation of the presence of dual elements in new urban planning concepts can be mentioned here. The application layer also includes all bipolar systems of infrastructural service of the area, which are already being designed; however, it also includes a search for bipolar historical and symbolic functions of cities, as well as elements of constructing the cultural landscape and identity of places.

The novelty of this article also manifests itself in the revealing of multiple, multi-area references and borrowings in the formation of spatial dualisms in the past and in the present. Artists, even those unambiguously associated with their architectural-urban achievements, combine symbolic, allegorical, and social themes in their work. Similarly, sociologists and the great utopians of social ideas move in the urban background, often using these ideas in their description of architectural elements par excellence.

The dualisms in our conceptual system allow us to understand their role more fully in the world and to create, as Florian Znaniecki put it, ‘spatial values’ (Znaniecki, 1938, p. 91), which include both occupied and empty spaces, interiors and exteriors, and anything that opposes itself.

Authors’ contributions

Conceptualisation: J.W.K. and P.F.Z.; methodology: J.W.K. and P.F.Z.; validation: J.W.K. and P.F.Z.; formal analysis: J.W.K. and P.F.Z.; investigation: J.W.K. and P.F.Z.; resources: J.W.K. and P.F.Z.; data curation: J.W.K. and P.F.Z.; writing – original draft preparation: J.W.K. and P.F.Z.; writing – review and editing: J.W.K. and P.F.Z.; visualisation: J.W.K. and P.F.Z.; supervision: J.W.K. and P.F.Z.; project administration: J.W.K. and P.F.Z.

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

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CYKLICZNOŚĆ DUALISTYCZNYCH TRENDÓW W PROJEKTOWANIU URBANISTYCZNYM. ANALIZA HISTORYCZNA POSTAW TWÓRCZYCH WYBRANYCH MISTRZÓW NA PRZESTRZENI WIEKÓW

STRESZCZENIE

W artykule wykazano, że tendencje dualistyczne są trendem okresowym i cyklicznym, powtarzanym przez wielu planistów i architektów na przestrzeni wieków. Należy zatem założyć, że w kolejnych koncepcjach miast przyszłości powyższe tendencje również będą obecne. Ma to istotne implikacje dla rozwoju myśli urbanistycznej w nadchodzących czasach. W artykule autorzy poruszyli problematykę dualnych rozwiązań w projektowaniu urbanistycznym i rozwoju miast. Należy już na wstępie zaznaczyć, że samo pojęcie dualności nie jest oczywiste i jednoznaczne. Liczne istniejące definicje są bardzo ogólne. Można wyróżnić wiele dyscyplin i obszarów nauki, w których występuje lub może pojawić się pojęcie

dualizmu. Jednocześnie definicja każdego z tych zjawisk będzie inna w zależności od obszaru, na którym występuje. Stąd autorzy dokonali daleko idącej redukcji typów dualizmów, zawężając obszar badań do postaw twórczych urbanistów, filozofów przestrzeni, artystów i architektów w ujęciu historycznym. Celem poszukiwania cech dualnych w formach przestrzennych jest znalezienie klucza do lepszego zrozumienia praw rządzących procesem planowania i urbanizacji. Weryfikacja przeciwieństw i dualnych cech odbywa się na trzech poziomach: wspólnoty, formy i funkcji. Warunki miejskie przyczyniają się do powstawania nowych jakości i nowych form przestrzennych, które pozwalają na nowo zdefiniować miasto i jego rozwój. Podstawą artykułu jest teza, że dualizm jest trwałą cechą rozwiązań przestrzennych (cechą powracającą) na przestrzeni dziejów.

Słowa kluczowe: przestrzeń miejska, dualizm przestrzenny, urbanistyka, historia struktur miejskich, dychotomia w przestrzeni miejskiej

BRIDGE MANAGEMENT SYSTEMS: AN OVERVIEW AND COMPARISON

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ABSTRACT

Bridges are one of the key elements of the transportation infrastructure of each country, and the reliability of the entire transportation network depends on their functioning. Maintaining bridges in proper technical condition is the main task of bridge management, for which more and more countries use bridge management systems (BMS). This study is devoted to comparing different BMS, reviewing the main functions and modules and determining the perspectives of development and implementation of the latest technologies in BMS. The analysed bridge management systems were compared by functions such as storage of bridge passport data, initial information on the bridge condition, assessment of the bridge condition, forecasting of the bridge condition and consideration of different maintenance strategies. Some systems are distinguished by the fact that they can predict future bridge condition, offer optimal maintenance strategies and take into account losses not only for the operation of structures, but also for transportation. Prospects for the development of BMS were also identified: the use of neural networks, the introduction of building information modelling (BIM) and the Internet of Things (IoT).

Keywords: bridge management systems, management, bridge, comparison

INTRODUCTION

Bridges are recognised as one of the key elements of road and rail infrastructure, and the efficiency of the entire transportation network system depends on their technical condition. The dynamics of increasing the number of bridges per year by about 1% of the total number of existing bridges indicates constant growth in the need for their maintenance and diagnostics (Bień & Salamak, 2022).

Bridge management systems (BMS) are used in many countries to ensure the operational readiness of bridges. A BMS includes a register of all bridges and is a database formed based on information collected during regular inspections and maintenance. Such a toolkit allows stakeholders to obtain complete information on the condition of bridge facilities under their control and make informed decisions on maintenance and operation (Ryall, 2010).

Bridge management covers all stages of the bridge life cycle – from design to reconstruction – and is focused on ensuring safe and efficient operation.

Developed countries such as the United States, Switzerland, Sweden, Norway, Finland (Mirzaei, Adey, Klatter & Thompson, 2014), China (Wan et al., 2019) and others have successfully used bridge management

systems for many decades. While developing countries have primarily focused on the construction of new bridges, the use of BMS in them has only been introduced in the last decade (Bodnar, Panibratets, Zavorodniy & Borysenko, 2018; Joshi, 2023).

BACKGROUND

Ryall (2010) defines six stages of the bridge life cycle, divided into two main groups: preventive management and regular maintenance and repair. Figure 1 shows the distribution of bridge life cycle stages.

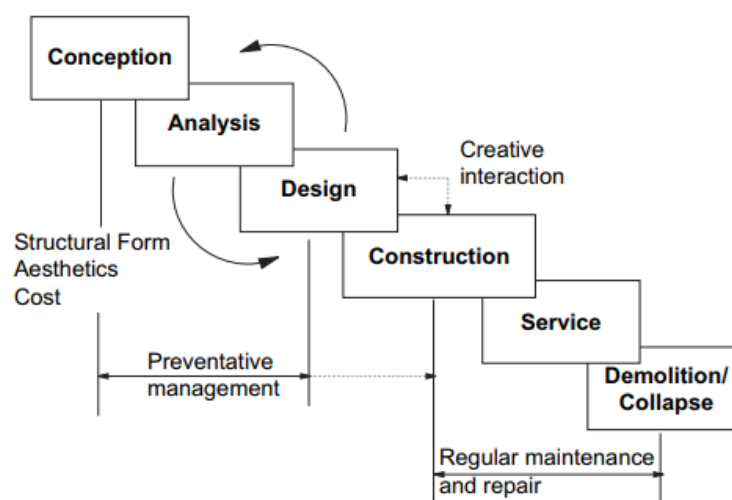


Fig. 1. Stages of the bridge life cycle

Source: Ryall (2010).

Most bridge management activities begin after a bridge is put into operation. The first stage involves collecting data about the bridge after the construction process is completed. The next stage adds information from regular inspections, maintenance and repairs. Parameters such as bridge materials, current and previous conditions, rate of deterioration, traffic volume location and conditions of the structure are used to estimate the projected real-life service life and load capacity, as well as prioritise financial resources for maintenance and repair.

Every year, the cost of maintaining the operational condition of each bridge and the entire bridge complex increases. Given the limited budgetary resources, the responsible services must prioritise bridge maintenance and inspection. For this purpose, bridge management systems are used, which provide a complete set of information on each facility and, in some cases, allow for the prioritisation and forecasting of bridge conditions in the short and long term.

It is important to note that the objective of a bridge management system is not to keep bridges in the best possible condition, but to prevent significant deterioration – which can lead to high maintenance costs. In the long term, it is best to maintain bridges in “average” condition from year to year at the lowest cost (Söderqvist & Veijola, 1998).

RESULTS

Implementation of bridge management systems in the world

Bridge management systems are key in ensuring that bridges are effectively maintained and scheduled for necessary maintenance and inspections. However, for a long period, the implementation of such systems was limited, relying instead on paper-based data and, in most cases, the absence of any accounting and management system. Maintenance was performed only after significant damage or destruction of the structure.

The first bridge management system was developed in the United States. In 1968, the Federal Highway Administration created the National Bridge Inspection Group, which developed a prototype bridge management system – the National Bridge NBI (Wan et al., 2019). Other countries later created their own BMS based on these existing developments.

Sweden has the most experience in bridge management, having started a comprehensive approach to bridge maintenance in 1944. Many of the surveys conducted in Sweden are stored in various archives (Racutanu, 1999). However, the actual implementation of bridge management systems in the modern sense started later.

In many cases, the creation of bridge management systems was triggered by the destruction of one or more bridges to avoid sudden and unpredictable accidents on these structures in the future. A series of bridge failures in the 1960s in the United States drew public attention to the problem of bridge conditions and prompted the Federal Government to develop a unified bridge inspection procedure that eventually evolved into the PONTIS bridge management system (Thompson, Small, Johnson & Marshall, 1998).

Another important reason for the introduction of bridge management systems is the accumulation of many bridges with limited information about their condition, which has led to the fact that maintaining existing bridges has become more expensive than building new ones (Miyamoto, Kawamura & Nakamura, 2000).

Many countries began implementing bridge management systems in the late 20th century, and this process continues to this day. Every year, the number of countries developing their own systems or using the experience of other countries increases. Figure 2 shows the launch years of the first and current versions of bridge management systems. It can be concluded that every year, more and more countries or individual administrations implement bridge management systems that are being improved and expanded.

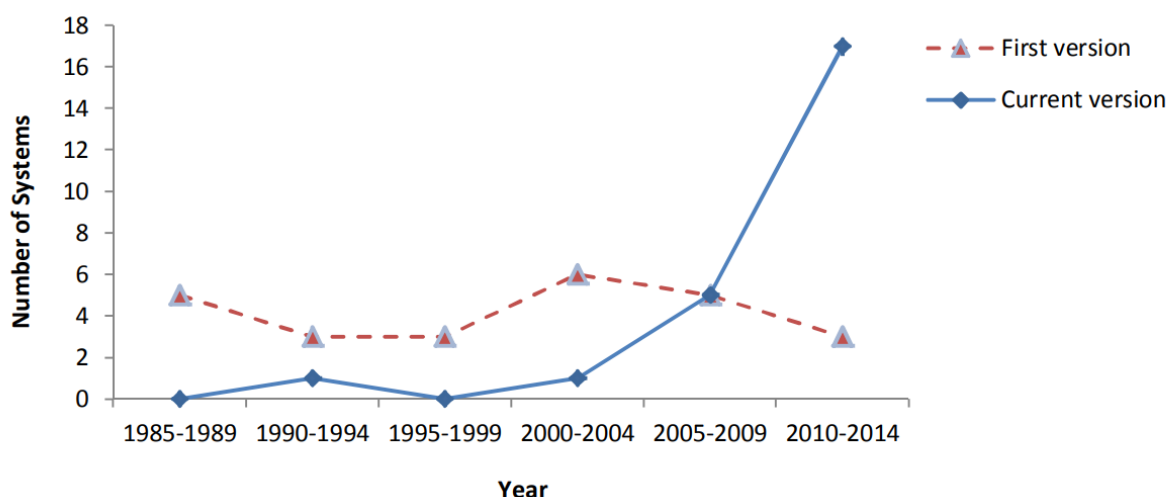


Fig. 2. Years of first and current versions

Source: Mirzaei et al. (2014).

At the same time, there are countries, such as Iran (Gholami, Sam & Yatim, 2013) and Serbia (Folić & Partov, 2020b), that are only now actively trying to implement bridge management systems to keep their bridge assets in good condition.

Structure of a modern bridge management system

The structure of modern bridge management systems is similar in most cases. Most are modular, allowing each system to include or exclude certain modules depending on specific needs. However, in all of these systems, the main module is the inventory module, based on which other modules function (Powers, Frangopol, Al-Mahaidi & Caprani, 2018).

According to Woodward et al. (2001), an effective bridge management system should include at least the following modules:

- inventory of the stock;
- knowledge of bridge and element conditions and their variation with age;
- evaluation of the risks incurred by users (including assessment of load-carrying capacity);
- management of operational restrictions and the routing of exceptional convoys;
- evaluation of the costs of the various maintenance strategies;
- forecast the deterioration of conditions and the costs of various maintenance strategies;
- socio-economic importance of the bridge (evaluation of indirect costs);
- optimisation under budgetary constraints;
- establishment of maintenance priorities;
- budgetary monitoring on a short- and long-term basis.

At the same time, according to a study by Ryall (2010), an effective bridge management system (Fig. 3) requires modules that include:

- inventory;
- inspection;
- maintenance;
- costs;
- bridge condition.

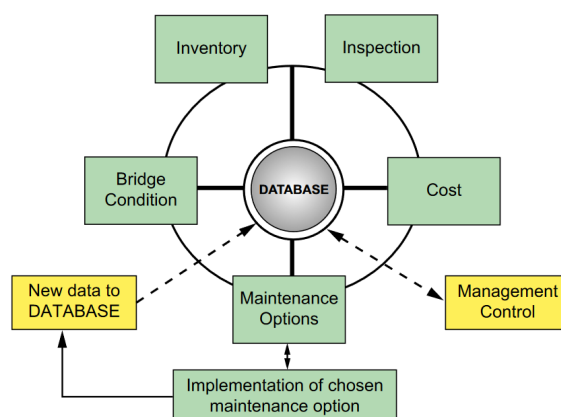


Fig. 3. A basic bridge management system

Source: Ryall (2010).

In general, bridge management systems can be categorised into three types depending on which modules they include (Dullah, Ghazali & Jausus, 2014). Type 1 is the simplest, while Type 3 is the most comprehensive representative of bridge management systems (Table 1).

Table 1. Groups of bridge management system components

Type 1	database/inventory inspection
Type 2	database/inventory inspection maintenance life-cycle cost
Type 3	database/inventory inspection maintenance life-cycle cost prediction model

Source: Dullah et al. (2014).

Comparison of modern bridge management systems

Subsequently, the bridge management systems of different countries, including the United States, Canada, China, Japan, Vietnam, Ukraine, Korea, Australia, Italy, Poland and others, were analysed (Söderqvist & Veijola, 1998; Thompson et al., 1998; Miyamoto et al., 2000; Woodward et al., 2001; Bjerrum & Jensen, 2006; Hallberg & Racutanu, 2007; Ryall, 2010; Dullah et al., 2014; Mirzaei et al., 2014; Chuang & Yau, 2017; Liao et al., 2017; Bodnar et al., 2018; Wan et al., 2019; Folić & Partov, 2020b, 2020a; Bello, Popescu, Blanksvärd & Täljsten, 2021; Joshi, 2023). In total, 34 bridge management systems were reviewed, analysed (Table 2) and compared by the following functions:

- bridge passport;
- survey data;
- inspection history;
- bridge condition assessment;
- cost of maintenance;
- transportation costs;
- forecasting the future condition of the bridge;
- maintenance planning.

Bridge condition assessment includes assessments performed directly in the bridge management system and by inspectors. Maintenance planning considers both short-term and long-term planning.

Most bridge management systems have similar functionality, and only a few systems exhibit exceptional features by not storing survey data and providing limited information about previous surveys. This can be considered an exception to the rule rather than a general standard. One of the “rarest” features is the ability to calculate transportation costs. This means that the system can calculate additional costs for road users in case of a bridge’s improper condition or destruction.

The prospects for the development of bridge management systems are broad. One of the development areas is using neural networks to predict the condition of bridges, assess their condition and identify factors that affect their deterioration (Trach et al., 2022, 2023). The introduction of building information modelling

Table 2. Comparison of bridge management systems

Country	Name	Passport of the bridge	Inspection data	History of inspections	Bridge condition assessment	Maintenance costs	Transportation costs	Bridge condition forecasting		Maintenance planning
								Deterioration	Shortening	
Australia	MRWA	+	+	+	+	+	-	+	+	+
Australia	NSW	+	+	+	+	+	-	+	-	n/a
Canada	GNWT	+	+	+	+	+	+	+	+	+
Canada	OBMS	+	+	+	+	+	+	+	+	+
Canada	QBMS	n/a	+	+	+	+	+	+	+	+
Canada	eBMS	+	+	+	+	+	+	+	+	+
Canada	PEI BMS	+	+	+	+	+	+	+	+	+
China	CMBS	+	+	+	+	n/a	n/a	n/a	n/a	n/a
Denmark	DANBRO/DANBRO+	+	+	+	+	+	-	+	+	+
Finland	FBMS	+	+	+	+	+	-	+	+	+
France	OA-MeGA	+	-	-	+	-	-	+	n/a	+
Germany	GBMS	+	+	+	+	+	+	+	+	+
Germany	SIB-Bauerwerke	+	+	+	-	-	-	+	n/a	+
India	IBMS/UBMS	+	+	+	+	n/a	-	+	n/a	+
Ireland	Eirspan	+	+	+	+	+	-	-	-	+
Italy	APTbMS	+	+	+	+	+	-	+	+	+
Japan	RPIBMS	+	+	+	-	+	+	+	+	+
Korea	KRMBS	+	+	+	+	+	-	+	+	n/a
Latvia	Lat Brutus	+	+	+	+	+	-	+	+	n/a
Malaysia	JKR BMS	+	+	n/a	-	-	-	-	-	-
Netherlands	DISK	+	+	-	+	+	+	-	-	+
Norway	BRUTUS	+	+	+	+	+	+	+	+	+
Poland	SZOK	+	+	-	+	-	-	+	-	+
Poland	SMOK	+	+	+	+	+	-	+	+	+
Spain	SGP	+	+	+	+	+	+	-	-	n/a
Sweden	BaTMan	+	+	+	+	+	+	+	+	+
Sweden	Safebrow	+	-	-	+	+	+	+	n/a	+
Switzerland	KUBA	+	+	+	+	+	-	+	+	+
Taiwan	TBMS	+	+	+	+	-	-	n/a	n/a	+
Ukraine	AEBMS	+	+	n/a	+	+	-	+	-	+
UK	NATS	+	+	+	+	n/a	-	-	-	+
USA	ABIMS	+	+	+	+	+	-	-	-	+
USA	PONTIS/AASHTOWare	+	+	+	+	+	-	+	+	n/a
Vietnam	Bridgeman	n/a	+	+	+	+	-	-	-	n/a

Source: own work.

(BIM) can also improve bridge management by allowing analysis of not only the description of damage and its assessment, but also tracking its development over time and a better understanding of the cause and effect of its occurrence. However, the implementation of BIM requires significant amounts of server space due to the large size of the models and a large amount of work to digitise and model existing bridges (Wan et al., 2019).

The prospects for the development of bridge management systems are broad. One of the development areas is using neural networks to predict the condition of bridges, assess their condition, and identify factors that affect their deterioration (Trach et al., 2022, 2023). The introduction of building information modelling (BIM) can also improve bridge management by allowing analysis of not only the description of damage and its assessment, but also tracking its development over time and a better understanding of the cause and effect of its occurrence. However, the implementation of BIM requires significant amounts of server space due to the large size of the models and a large amount of work to digitise and model existing bridges (Wan et al., 2019).

Another promising direction is the use of IoT technologies, which can provide an opportunity to obtain more data on the condition of bridges in real-time while also contributing to the efficiency of bridge management systems.

CONCLUSIONS

This study examined modern bridge management systems that are used to ensure bridge safety and improve the efficiency of their maintenance. The basic functionality typical for each system was analysed, and the features of some systems that can predict future states of structures, take into account traffic losses and offer optimal maintenance strategies were highlighted. The use of such systems can improve traffic safety and reduce bridge maintenance costs. However, it should be noted that the development and implementation of such systems require significant financial and technical resources.

Potential areas of development include the integration of the latest technologies, the development of forecasting and decision-making systems using neural networks, the introduction of BIM and the use of the IoT. In general, developing and implementing new capabilities in bridge management can further improve the safety and efficiency of transport infrastructure.

Authors' contributions

Conceptualisation: R.T. and V.T.; methodology: T.W.; validation: T.W. and R.T.; formal analysis: V.T. and R.T.; investigation: V.T.; resources: V.T.; data curation: V.T.; writing – original draft preparation: V.T.; writing – review and editing: R.T. and T.W.; visualisation: V.T.; supervision: T.W. and R.T.; project administration: V.T.; funding acquisition: V.T. and T.W.

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

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SYSTEMY ZARZĄDZANIA MOSTAMI: PRZEGLĄD I PORÓWNANIE

STRESZCZENIE

Mosty są jednym z kluczowych elementów infrastruktury transportowej każdego kraju i od ich funkcjonowania zależy niezawodność całej sieci transportowej. Utrzymanie mostów w należytym stanie technicznym to główne zadanie zarządzania mostami, do którego realizacji coraz więcej krajów korzysta z systemu zarządzania mostami (BMS). Niniejsze opracowanie poświęcone jest porównaniu różnych systemów BMS, przeglądowi głównych funkcji i modułów oraz określeniu perspektyw rozwoju i wdrożenia najnowszych technologii w BMS. Analizowane systemy zarządzania mostem porównano pod kątem takich funkcji, jak: przechowywanie danych paszportowych mostu, wstępna informacja o stanie mostu, ocena stanu mostu, prognozowanie stanu mostu oraz uwzględnienie różnych strategii utrzymania. Niektóre systemy wyróżniają się tym, że potrafią przewidzieć przyszły stan mostu, oferują optymalne strategie konserwacji i uwzględniają straty w eksploatacji konstrukcji. Zidentyfikowano także perspektywy rozwoju BMS: wykorzystanie sieci neuronowych, wprowadzenie modelowania informacji o budowaniu (BIM) oraz internetu rzeczy (IoT).

Słowa kluczowe: systemy zarządzania mostem, zarządzanie, most, porównanie

THE BREEAM, THE LEED AND THE DGNB CERTIFICATIONS AS AN ASPECT OF SUSTAINABLE DEVELOPMENT

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ABSTRACT

Some of the most significant problems of industrialised countries are increasing consumerism, the growing demand for more and more energy and other natural resources, and the depletion of non-renewable sources. The visible consequences are environmental pollution and global warming. To address these issues, there is growing pressure on the use of alternative energy sources, the use of natural resources and the introduction of new technologies. The use of multi-criteria building certification systems, which evaluate their performance, is becoming increasingly common in the building industry. The BREEAM, the LEED, and the DGNB are among the most popular methods for assessing sustainable architecture, and they are project management tools. The main task of the article was to define and describe the impact of documents related to sustainable development certificates on contemporary design and living and working conditions, as well as to demonstrate the relationship between the quality of architecture and environmental protection. Another goal is to indicate how dynamically the number of certificates issued in Poland is increasing. The study used the necessary research methods: analysis and criticism of applicable documents and literature, as well as an intuitive method based on personal experience. The scope of the work includes a discussion of the most frequently obtained certificates: the BREEAM, the LEED, and the DGNB, the achievements of which prove the use of solutions conducive to sustainable development.

Keywords: sustainable development, BREEAM, LEED, DGNB, architecture, sustainable architecture

INTRODUCTION

Authorities in industrialised countries are struggling with many problems, including increasing consumerism and growing demand for energy. The visible effects are environmental pollution and global warming. In recent years, there has been a clearly noticeable increase in interest in sustainable construction (Runkiewicz, 2010). EY – an international concern providing audit services, tax, business, and transaction consulting, as well as belonging to the so-called Big Four – emphasises the huge role of sustainable development and environmental, social and governance (ESG) in their corporate social responsibility strategy (CSR) statute. Currently, business development is related to social responsibility and must be carried out while protecting natural resources and contributing to society (EY, [n.d.]). The European Union is striving to achieve climate neutrality, which is why the share of renewable energy is increasing. According to Eurostat Statistics Explained 2021 (Renewable energy statistics), renewable energy satisfied 19.7% of final consumption in 2019. The leading sources are wind and water, and a rapidly developing sector is solar energy (Eurostat,

2023). The way of designing and building is also changing – the popularity of wood as a building material is growing. Research by the European Forest Institute (EFI) indicates that the production of 1 t of steel causes the emission of 2 t of CO₂, and 1 t of cement causes 1 t of CO₂; therefore, the use of 1 t of wood allows for a reduction of CO₂ emissions by 2 t (Hurmekoski, 2018). There is a visible trend towards modular design and broadly understood prefabrication, which can reduce construction costs. Highly developed technology can also become very energy efficient.

The main task of the article is to indicate the impact of the certificate system on working conditions and the relationship between architectural quality and environmental protection.

The first and most basic goal of the article was to examine the impact of the increasingly widespread certification of buildings related to sustainable development issues on contemporary design, as well as on housing and working conditions and secondly, to demonstrate the relationship between the quality of architecture, the design process, building use and environmental protection.

MATERIAL AND METHODS

The necessary research methods were used: analysis of literature and applicable documents, as well as observational and intuitive methods – based on personal experience in designing BREEAM-certified office buildings. The issues that have the greatest impact on the contemporary design of commercial buildings were selected, and the changes that have occurred in recent years in the design of multi-family residential buildings have been described. The challenge of contemporary design is sustainable design, which, due to the provisions in documents and market requirements, becomes almost obligatory. The work discusses certification systems, the benefits of sustainable construction, the impact on design decisions, the well-being of users and residents, and increased market attractiveness. The scope of the work includes a discussion of general issues related to design in line with sustainable development and the most frequently obtained certificates: the BREEAM, the LEED and the DGNB, the achievement of which proves the use of solutions conducive to sustainable development.

SUSTAINABLE DEVELOPMENT AND THE DESIGNER'S ETHICAL RESPONSIBILITY

Designers are bound by contracts with their clients that cover the production of a specific project. However, there is also ethical responsibility, taking into account the impact of projects on the surrounding reality – both professional and personal. Including environmental issues among public safety, architects and urban planners should protect the ecosystem and maintain key resources. Saving and developing alternative energy sources is important, while ensuring the well-being of current and future generations is a comprehensive goal. A holistic view of buildings as individual systems in themselves and inextricably linked to the ecosystems surrounding them will allow us to understand the role of the facility in the ecosphere and enable us to make important design decisions (Bergman, 2012). From a systemic perspective, the environment is a set of objects with their features and the relationships between them (Chmielewski, 2010). Completing certification and implementing these types of facilities is obligatory, but it proves that the developer and user take a serious approach to environmental protection. The problem of research on the design and assessment of sustainable architecture is increasingly being addressed (Kamionka, 2012).

In dictionaries, sustainability is defined in terms of continuity, as bringing about or maintaining balance (Drabik, Kubiak-Sokół & Sobol, 2023). In the literature, the ESD phrase is used to monitor education for sustainable development. It is the UNESCO education sector's response to the urgent challenges facing the planet. Human actions have led to compounding threats that are becoming increasingly difficult to reverse (UNESCO, [n.d.]). The meaning of E oscillates between environmental, ecological, and economic;

D stands for development and also design; S stands for sustainable and sustainability. ESD is treated as a code expressing concern for sustainable development issues. In Western countries, it suggests social and cultural change. The problem is treated on a global scale and concerns the basic issue related to population growth and the resulting effects of human existence on Earth. Sometimes, the meaning of ESD includes actions aimed at mitigating the perceived adverse impact of trends towards economic globalisation (United Nations Conference on Environment and Development Rio de Janeiro, Brazil, 1992).

According to the strategy to reduce or limit carbon dioxide emissions by 2054, the efficiency of buildings is considered one of the basic elements that are essential in reducing the intensity of global warming (Pascala & Socolow, 2019). Existing research shows that the most important decisions are made at the initial stage of the design cycle and have the greatest impact on the life cycle cost of the building. Designers are, therefore, obliged to create more energy-efficient buildings (Stipo, 2015).

AN OUTLINE OF DOCUMENTATION RELATED TO SUSTAINABLE DEVELOPMENT AND CONSTRUCTION

The most important documents regarding the issue include Agenda 21 (Action Program – Agenda 21), adopted on the initiative of the UN in 1992 at the Second Conference in Rio de Janeiro, where the guiding act was the slogan: “Environment and development”. The document describes the protection and management of natural resources, the aim of which is to ensure lasting and sustainable development (United Nations Conference on Environment and Development Rio de Janeiro, Brazil, 1992). In Poland, the principle of sustainable development is enshrined in Article 5 of the Constitution of the Republic of Poland: “The Republic of Poland safeguards the independence and inviolability of its territory, ensures human and civil freedoms and rights as well as the safety of citizens, guards the national heritage and ensures environmental protection, guided by the principle of sustainable development.” (Dz.U. 1997 Nr 78 poz. 483). The definition itself was described in the Polish Environmental Protection Law: “It is understood as such socio-economic development in which the process of integrating political, economic and social activities takes place, while maintaining natural balance and the durability of basic natural processes, in order to guarantee the possibility of meeting the basic needs of individual communities or citizens of both the present generation and future generations.” (Dz.U. 2001 Nr 62 poz. 627).

In recent years, sustainable construction has become an important element of the construction industry. The Polskie Stowarzyszenie Budownictwa Ekologicznego (Polish Association of Ecological Buildings) defines a sustainable building as an economical, comfortable building created with respect for the natural environment. Green buildings should be designed in such a way as to simultaneously meet the needs of current users and future generations (Polskie Stowarzyszenie Budownictwa Ekologicznego [PLGBC], 2023e). The association’s website contains a database of certified buildings. According to the PLGBC Report from 2023, over 36 million m² of usable building space is subject to certification in multi-criteria systems (PLGBC, 2023f). Building assessment systems available in Poland are: the BREEAM, the Green Building Standard (GBS), the HQE, the LEED, the ZIELONY DOM, the WELL, and the DGNB. The GBS and the ZIELONY DOM are Polish multi-criteria assessments. The GBS is a building assessment system adapted to Polish conditions. It is important to promote user comfort and a high level of internal environments with rational energy consumption. The ZIELONY DOM (in English: green house) is a Polish multi-criteria assessment of residential buildings introduced in 2021.

Figure 1 shows the division of the usable area of certified buildings into individual systems, in accordance with the above-mentioned report. The three most popular systems in the world are the BREEAM (UK), the LEED (USA) and the DGNB (Germany). The first certificates in Poland were issued in 2010: four for office buildings located in Warsaw (two BREEAM at a very good level – Crown Square and Signum Work Station;

two LEED: Atrium City Deutsche Bank Green Branch – LEED gold level and Atrium City Skanska Office – LEED silver level) and two for logistics and industrial facilities (LEED silver level: Colgate-Palmolive Facility, Świdnica and BorgWarner Manufacturing Plant, Jesionka), (PLGBC, 2023a).

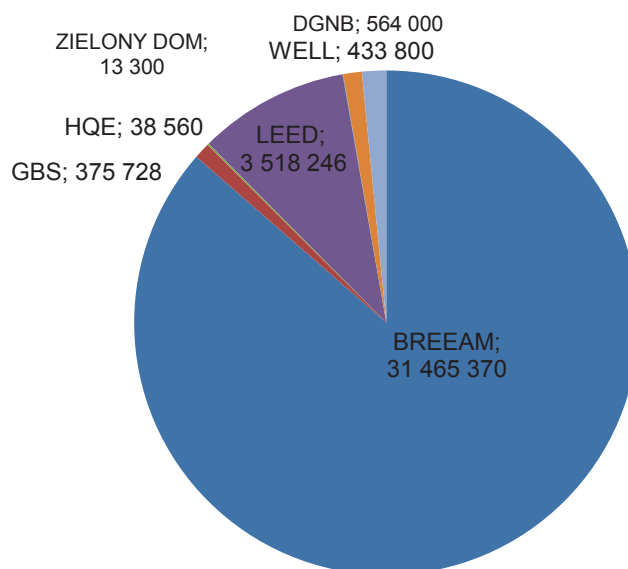


Fig. 1. Division of the usable area of certified buildings into individual systems in 2023

Source: own study based on the PLGBC (2023f).

Over the years, new legal regulations related to the design of low-energy buildings have appeared. In accordance with Directive 2010/31/EU of the European Parliament and of the Council, from 2019, all new public buildings in Member States must have almost zero energy consumption. Members of the European Union undertake to create national plans that aim to increase the number of such buildings. The definition of the term nearly zero energy building is as follows: “a building with very high energy performance [...]. The almost zero or very low amount of energy required should come to a very high extent from energy from renewable sources, including energy from renewable sources produced on-site or nearby” (Directive 2010/31/UE). In accordance with the applicable regulation on the detailed scope and form of the construction project (Dz.U. 2022 poz. 1679), the technical design must include energy characteristics, including the power balance of devices, thermal properties of external partitions, energy efficiency parameters of the installation and data indicating that the adopted construction and installation solutions meet the conditions for energy savings in accordance with applicable regulations.

In 2021, the European Union introduced the Fit for 55 package, which aims to achieve climate neutrality by 2050 and a 55 % reduction of net greenhouse gas emissions by 2030 (compared with 1990 levels). According to the Fit for 55 package, greenhouse gas emissions from industry and electricity have been significantly reduced thanks to the European Union Emissions Trading System (EU ETS). However, GHG emissions from the transport sector have remained stable over the last decade. Therefore, the directives include provisions on energy taxation (Council Directive 2003/96/EC), which will increase the prices of greenhouse gas emissions in the transport sector. The emphasis is on the use of renewable transport fuels in transport and the promotion of electromobility (Erbach & Jensen, 2024).

The BREEAM

The Building Research Establishment's Environmental Assessment Method (BREEAM) was the world's first system for assessing buildings in terms of sustainable development (1990, Building Research Establishment Global, UK). Currently, as an international standard, it is used in over 85 countries. In each country, the BREEAM is adapted and operated by local specialists. Thanks to this system, before the construction of the building, the developer has knowledge of the impact of the designed building on the environment, obtains information on the effective use of energy, and has the opportunity to ensure maximum thermal conditions and comfort for future users, as well as cheaper operation. The main goals of the system are buffering the impact of the building operation cycle on the environment, creating buildings in a way that is beneficial to the environment, creating a credible building label, and supporting innovation in the construction industry and its supply chain (BRE Global, 2021).

The BREEAM develops schemes to assess the environmental performance of buildings at various stages. The basic division concerns the distinction between newly designed buildings (new construction) and existing buildings (in-use – buildings existing and in use for at least two years). The system also enables certification covering renovation and finishing (refurbishment & fit-out), civil engineering and infrastructure (the CEEQUAL) and, in Great Britain, also newly built apartments (the Home Quality Mark). In order to illustrate the certification method, a new construction scheme for an office building was discussed (PLGBC, 2023b).

The completed buildings subject to evaluation receive a final percentage result that corresponds to a specific rating: outstanding $\geq 85\%$, excellent $\geq 70\%$ (Fig. 2), very good $\geq 55\%$, good $\geq 45\%$ pass $\geq 30\%$, unclassified $\leq 30\%$. When the developer decides to certify the building, an assessor is introduced to the design process and is responsible for coordinating the proceedings. Based on the point matrix specifying the level and the score in given BREEAM categories, guidelines for a given project are created. The assessor provides recommendations to the entire project team, collects evidence and creates reports confirming the clear compliance of the project with the relevant criteria defined in accordance with the adopted BREEAM scheme. Facilities are assessed in the following categories: management, health and well-being, threats, energy, transport, water, materials, waste, land use and ecology, pollution, and innovation. Certification uses flexible methods of scoring individual elements, which means that non-compliance in one area can be compensated in another. In the case of office buildings, depending on how the facility will be used, there are two certification options: shell and core, and fully fitted. It is the developer who decides which type will be considered. The first term refers to a project without a tenant area, while the second one applies to a project with a tenant area.

In the management category, points are awarded, among others, for design consultations, including with representatives of third parties at the conceptual design stage (strictly defined criteria). In the case of the health and well-being section, the guidelines include, among others, visual comfort, where the necessary condition is the use of lighting fixtures with fluorescent light sources equipped with high-frequency ballasts. Points are also awarded for designing a system that limits excessive sunlight (rollers, blinds). The diagram contains strictly defined criteria regarding the arrangement of rooms in terms of access to daylight, which involves analysis. The BREEAM guidelines specify, among others, the maximum distance from a window that a workstation can be located, and the location of conference rooms. Regarding air quality, it is essential not to use materials containing asbestos. The installation designer is obliged to prepare an indoor air quality plan to obtain the most favourable conditions for future users. Guidelines for ventilation and emissions from products used in the building are also specified. In the case of acoustics, an acoustician should be appointed at an early stage of the process to define design guidelines. Noise levels in individual rooms should meet minimum national requirements.



Fig. 2. The Bałtyk office building in Poznań (BREEAM certification level excellent): a – photo taken during the construction of the building, 2016; b – photo after the construction of the building was completed, 2017

Source: ©Anna Piętocha.

Safe access to the building should be provided for both pedestrians and cyclists. The designer must develop a strategy for access to the building for disabled people, people of different ages and genders, and parents with children by conducting consultations, among others, with future users and technical specialists. In terms of energy efficiency, at the stage of the design process, an analysis of the vertical transport system is performed, allowing the selection of the appropriate number and size of elevators, escalators and walkways, which also have energy-saving features. The category regarding alternative means of transport defines, among others, the development of the surrounding land by improving the layout of bicycle paths, equipping an appropriate number of parking spaces with electric vehicle charging stations, dedicated parking spaces for people using the car sharing system, as well as designing an appropriate number of bicycle racks with showers, changing rooms (with lockers) and drying rooms. In the case of the water category, points are counted using an appropriate calculator. Loans may be granted, for example, to equip sanitary facilities with devices with low water consumption or to install grey or rainwater utilisation systems. The water installation should include solutions that reduce water consumption.

The materials category provides a detailed specification of the main building elements. Information regarding the use of products from the materials sector covered by the environmental products declaration (EPD) certification and conducting an LCA analysis are important. The BREEAM guidelines also specify the durability and resistance of elements to external factors. The protection of sensitive elements should be ensured, as well as security of entrances, elevators, stairs, and vehicle manoeuvring areas – using, among others, bollards and barriers, as well as specialised solutions used to reduce the potential degradation of materials by environmental factors. In terms of waste, it is important to create appropriately sized waste storage zones for recycling and to finish floors and ceilings only when the tenant is known – to avoid wasting materials. The designer should create

a report specifying the adaptability of the building in the event of future functional changes. Regarding ecology, an ecologist's report should be created specifying the value of the area, as well as the greenery management plan prepared by a landscape architect. All valuable elements should be secured at the construction stage. One of the first certified commercial buildings in Poland was Plac Unii Lubelskiej in Warsaw (Fig. 3), with an area of 94,000 m² (APA Kuryłowicz & Associates), completed in 2013 – BREEAM very good (PLGBC, 2023a).



Fig. 3. Plac Unii Lubelskiej in Warsaw, 2024: a – view from the tram stop; b – view from Puławska

Source: ©Anna Piętocha.



Fig. 4. The Mickiewicz Estate in Warsaw, 2024 – the first BREEAM-certified housing estate in Poland

Source: ©Anna Piętocha.

Until recently, in Poland, mainly office buildings were certified, but more and more often, these are commercial, logistics, and warehouse buildings, as well as residential buildings (PLGBC, 2023a). The Mickiewicz Estate (Fig. 4) in Warsaw was the first BREEAM-certified housing estate in Poland (2016). The first stage was certified at a good level. According to data from Skanska, Residential Development Poland, which implemented the project, nearly 40% of clients declared that the certificate was an important factor when choosing an apartment (SKANSKA, 2023).

The LEED

The Leadership in Energy and Environmental Design (LEED) rating system was first introduced in 1998 in the United States by the U.S. Green Building Council (U.S. Green Building Council [USGBC], 2019). Currently, it is the most widely used system in the world (168 countries). In Poland, the LEED appeared in 2009 and is the second most frequently used certification system (PLGBC, 2023d). The aim of the system is to create buildings that will save money, create effective buildings with reduced carbon dioxide emissions and places that are healthier for people. Counteracting climate change is also crucial. Office, industrial, hotel, school and commercial spaces are certified.

The certification levels awarded are: platinum ≥ 80 points, gold 60–79 points, silver 50–59 points, and certified 40–49 points. Points are awarded in five basic categories: integrated design process, energy and environment; effective water management; materials and natural resources; quality of the internal environment; location and transport (max. 100 points); and in two additional ones: sustainable terrain, and innovation and regional priorities (max. 10 points). There are also critical points in each category (prerequisites), which are obligatory, e.g. the use of the HVAC system (PLGBC, 2023d).

The certification includes the following categories: Building Design and Construction (BD+C), Interior Design and Construction (ID+C), Building Operations and Maintenance (O+M), and Neighbourhood Development (ND), Homes, Cities. Similarly to BREEAM, the basic BD+C category includes LEED New Construction (for newly constructed buildings), and LEED Core&Shell (common areas in new buildings) for schools and retail, etc.

The certification process is divided into the design and implementation phases (until the building is put into use), in which the design team, LEED AP, and the developer actively participate. In the implementation phase, an additional person is appointed responsible for coordinating the work (commissioning agent), acceptances, reports, and procedures.

The first certified building in Poland was the logistics and industrial facility BorgWarner Manufacturing Plant in Jasionka, Podkarpackie Voivodeship, with an area of 7,000 m² (LEED New Construction Silver) completed in 2008, certified in January 2010 (PLGBC, 2023a).

The DGNB

The DGNB Certification System is the youngest of the three systems discussed and is present in 21 countries. It was created in Germany in 2008 on the initiative of the Deutsche Gesellschaft für Nachhaltiges Bauen (German Sustainable Building Council). An accredited auditor takes part in the process (PLGBC, 2023c). The system is divided into schemes for individual buildings and regions (e.g. industrial areas). The DGNB covers six key aspects of sustainable construction: environmental, economic, socio-cultural, functional, technological, process and location quality. The first four have equal weight in the assessment: 22.5%, the next 10%. This system defines objectives that contribute to the building's overall performance depending on the degree to which they are met (Gesellschaft für Nachhaltiges Bauen [DGNB], 2014).

This system aims to increase the quality of life and well-being of users, reduce costs, reduce additional costs, reduce greenhouse gas emissions and waste, and make planning more efficient. The documents developed

indicate to consultants and manufacturers the extent to which construction products influence the durability of the project, which thus contributes to further sustainable development.

The DGNB certification process takes place in four steps: preparation and registration, documentation submission, compliance check, and results and certification. In the first stage, the client contacts the auditor and signs the contract; in the second stage, the auditor completes the necessary documents; in the third stage, the DGNB Certification Team checks the content of the submitted documentation, then sends a report to the auditor, who sends an official statement to DGBN or fills in the gaps. The commission will confirm the next test result is confirmed by the commission. The certification notice is then sent to the client and the auditor. The official presentation of the certificate usually takes place during trade fairs, congresses or building openings. The final rating is as follows: $\geq 35\%$ bronze (only for existing buildings), $\geq 50\%$ silver, $\geq 65\%$ gold, $\geq 80\%$ platinum.

RESULTS AND DISCUSSION

As a result of the studies carried out, it was possible to show how important a role the aspect of sustainable development plays in contemporary design. Further detailed research is required. Green building certificates are relatively new design guidelines that lead to the introduction of standards in the design of sustainable buildings. The evaluation systems for the discussed certificates are presented below in tabular form (Fig. 5).

BREEAM rating			Score [%]	
Outstanding	*****		≥ 85	
Excellent	****		≥ 70	
Very Good	***		≥ 55	
Good	**		≥ 45	
Pass	*		≥ 30	
Unclassified	–		< 30	

LEED rating		Points earned	
Platinum		$80+$	
Gold		$60-79$	
Silver		$50-59$	
Certified		$40-49$	

DGNB rating		Score [%]	
Platinum		≥ 80	
Gold		≥ 65	
Silver		≥ 50	
Bronze		≥ 35	

Fig. 5. Rating systems of the BREEAM, the LEED and the DGNB

Source: own work.

According to the 2022 Report, 1,359 certified buildings were built in Poland, most of them in the Masovian Voivodeship (572), then the Małopolskie Voivodeship (130) and the Silesian Voivodeship (122), (PLGBC, 2023f). This result represents 45% of all buildings certified in Central and Eastern European countries (followed by: the Czech Republic – 562, Romania – 375, Hungary – 262). There is a growing interest in certification systems for developers of multi-family buildings. As of the date of preparation of the above-mentioned report, the number of all certified residential buildings was 118 (106 BREEAM, 7 LEED, 5 HQE), of which 29 buildings were completed in 2022. After the commencement of the COVID-19 pandemic, there was noticeably increased demand from the e-commerce sector (online trade) for warehouse and industrial areas. In the period from March 2021 to March 2022, 171 certificates were awarded in this sector, with the total amount being 398. Also, due to the pandemic, the WELL Health & Safety Rating certificates focusing on the health-promoting features of buildings have gained popularity. However, there is a visible decline among commercial facilities – only four certificates were issued in the analysed period (45 in the previous year).

Designers are increasingly willing to use long-lasting building materials. In the case of certified buildings, it is important that the products have an EPD declaration, which considers the transport of the raw material from

the extraction point to the factory and to the construction site, the carbon dioxide equivalent in the production process, the durability of the material and the possibility of recycling or reusing. The implementation of certified buildings is also related to the need to meet additional criteria on the part of the construction site, e.g. in the case of the BREEAM, the general contractor is bound by the Environmental and Social Code of Conduct for contractors (proper and safe access, good neighbourhood, ecological awareness, safe and comfortable working conditions), construction site impact (e.g. monitoring and reporting CO₂ emissions of construction works and transport) and construction waste management – the requirement to prepare and implement the site waste management plan (Jaczewski, 2014).

During the lockdown, public awareness of the climate crisis and the need to actively counteract this phenomenon increased. According to the Polskie Stowarzyszenie Budownictwa Ekologicznego (PLGBC) survey, 60% of office workers expect their employers to implement sustainable strategies in the work environment; 83% of developers expect more demand for the rental of sustainable buildings, where tenants expect operational savings as well as the use of comfortable interiors (PLGBC, 2023f). Green buildings also improve user comfort. For example, provisions on the maximum distance of the desk from the daylight source prevent substandard solutions. Thanks to specific criteria, BREEAM-certified office buildings include cyclists' locker rooms, clothes dryers, bicycle racks, electric car charging areas, and green roofs. Figure 6 shows how dynamically the number of certified buildings in Poland has been growing in recent years. In 2016, 81 green building certificates were issued, and 273 in 2022 (Fig. 6).

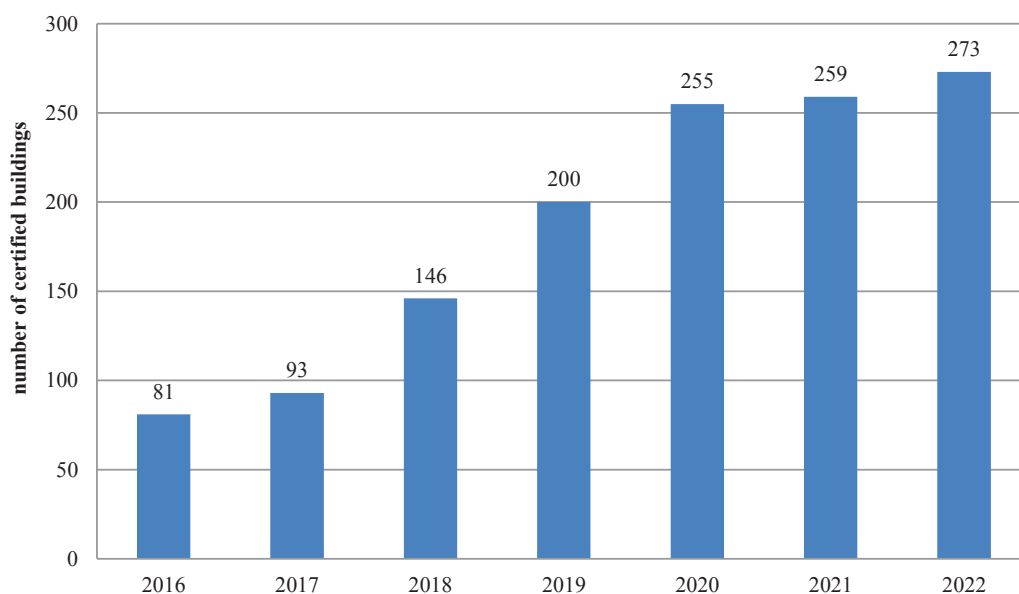


Fig. 6. Number of certified buildings in Poland in a given year. The period covers the time from March to March

Source: own study based on the PLGBC (2023f). Chart prepared on the basis of the Polskie Stowarzyszenie Budownictwa Ekologicznego (PLGBC) reports published since 2015.

Office buildings in Poland gave rise to building certification in Poland and constitute over 42% of all certified buildings. However, recently there has been an annual decline in their number. However, the share of the housing sector is increasing. The share of other buildings in the 2023 Report (PGLBC, 2023f) has basically not changed (Fig. 7).

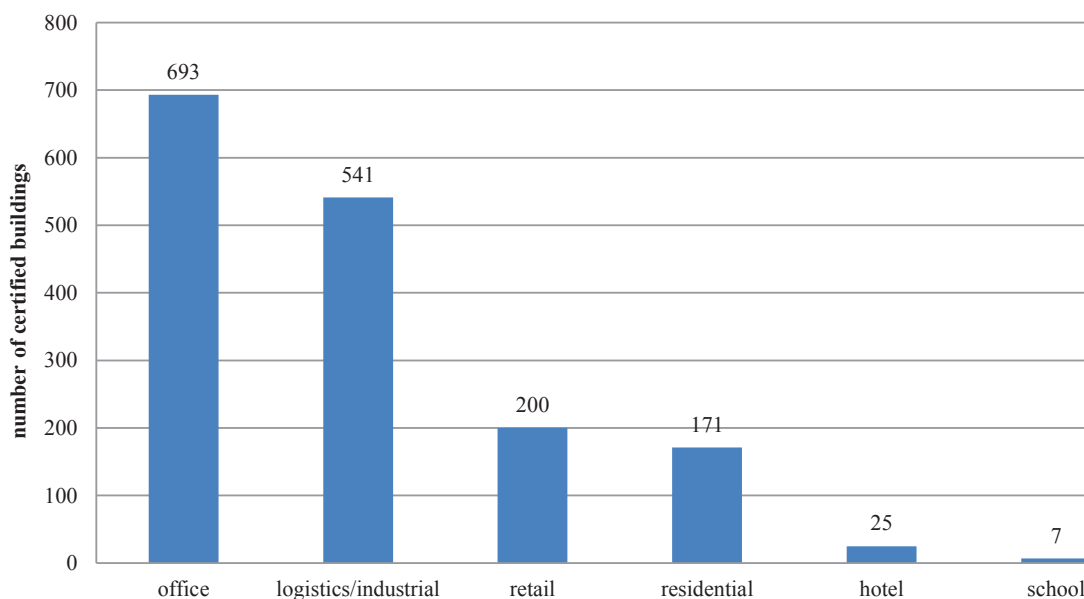


Fig. 7. Industry division of certified buildings in Poland in 2023

Source: own study based on the PLGBC (2023f).

The emerging multi-family residential buildings allow their users to save on costs and function in balance with nature, where comfortable green zones are designed, with green roofs utilising rainwater, and bird and insect boxes installed, along with photovoltaic panels on the roofs. Figure 7 shows that hotels and schools in Poland are also starting to be covered by certificates.

CONCLUSIONS

The certification process and adapting a project to the guidelines is time-consuming and is often associated with increased financial outlays. Certificates contribute to the increase in the market value of the building, both in the case of rental and sale. However, it should be noted that an economical operation largely depends on the way this type of building is managed. In certified buildings, construction costs are higher, but rent rates are also higher. Many international corporations have provisions in their CSR statutes that leased office space must be located only in certified buildings. Analysis of the reports of the Polskie Stowarzyszenie Budownictwa Ekologicznego (PLGBC) shows a huge increase in the number of buildings being constructed with this type of certificate, which has changed the way of design in recent years. In a dynamically changing reality, a building certificate is no longer optional, but in the case of office buildings, even obligatory – it is increasingly becoming a basic market requirement.

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CERTYFIKACJE BREEAM, LEED I DGNB JAKO ASPEKT ZRÓWNOWAŻONEGO ROZWOJU

STRESZCZENIE

Do największych problemów krajów uprzemysłowionych należy zaliczyć postępujący konsumpcjonizm, rosnące zapotrzebowanie na coraz większą ilość energii i innych zasobów naturalnych oraz wyczerpywanie się nieodnawialnych źródeł. Widocznymi skutkami są zanieczyszczenie środowiska i globalne ocieplenie klimatu. Ograniczoność zasobów może prowadzić do globalnego kataklizmu. W celu przeciwdziałania wymienionym problemom coraz większy nacisk kładziony jest na wykorzystywanie alternatywnych źródeł energii, korzystanie z zasobów naturalnych oraz wdrażanie nowych technologii. Coraz powszechniej stosowane są w budownictwie systemy certyfikacji wielokryterialnej budynków, które oceniają ich wydajność. Do najpopularniejszych metod oceny zrównoważonego budownictwa należą BREEAM, LEED i DGNB – stanowią narzędzie zarządzania projektem. Głównym zadaniem artykułu jest zbadanie, jaki wpływ na współczesne projektowanie i warunki mieszkaniowe czy pracy mają dokumenty związane z certyfikatami zrównoważonego rozwoju, a także wykazanie związku między jakością architektury a ochroną środowiska naturalnego. Kolejnym celem jest wskazanie, jak dynamicznie zwiększa się liczba wydawanych tego typu certyfikatów w Polsce. W badaniu zastosowano niezbędne metody badawcze: analizę i krytykę obowiązujących dokumentów oraz literatury, a także metodę intuicyjną opartą na osobistym doświadczeniu. Zakres pracy obejmuje omówienie najczęściej uzyskiwanych certyfikatów: BREEAM, LEED i DGNB, których uzyskanie świadczy o zastosowaniu rozwiązań sprzyjających zrównoważonemu rozwojowi.

Słowa kluczowe: zrównoważony rozwój, BREEAM, LEED, DGNB, architektura, budownictwo zrównoważone

THE STRENGTH OF COMPLEX COMPRESSED REINFORCED CONCRETE STRUCTURES UTILISING HOLLOW CONCRETE BLOCKS

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ABSTRACT

Structures in which elements from different materials work together are successfully used in various combinations. Recently, new, effective construction materials and products have appeared. In complex or multi-component structures, elements made of materials with different physico-chemical or strain-strength characteristics should be sensibly combined for joint work. The more fully the properties of the components' materials are utilised, the more efficient the design itself is. By analysing global practice, it can be seen that small concrete blocks have become widespread. The use of masonry made of hollow concrete blocks in modern construction differs from traditional ones in that the void area (up to 70%) makes it possible to create complex high-strength load-bearing structures by filling them with monolithic reinforced concrete. This also enables speeding up the construction process itself and reducing the cost of work on the construction site. The purpose of the study was to examine the strength of centrally compressed columns composed of hollow blocks and concrete filling with different transverse and longitudinal reinforcements, as well as to improve their calculation methodology. Experimental studies of centrally compressed columns, with different percentages of reinforcement using hollow concrete blocks as permanent formwork, have been carried out. The article presents the results of the research on strength, but the results of the strain studies were not included in this work. The proposed method of calculating complex constructions can be applied in design practice. A good correlation was observed between the experimental results and the results of the analytical model.

Keywords: compression behaviour, reinforced concrete column, hollow concrete blocks

INTRODUCTION

When designing structures where various components, including blocks, masonry mortar, concrete filling voids and reinforcement work together, questions may arise as to how these structures relate to two building regulation documents: EN 1996-1-1:2005+A1:2012 (European Committee for Standardization [CEN], 2012) and EN 1996-2:2006 (CEN, 2006a).

In the building regulation documents EN 1996-1-1:2005+A1:2012 (CEN, 2012), EN 1992-1-1:2004 (CEN, 2004), EN 1996-2:2006 (CEN, 2006a), EN 1996-3:2006 (CEN, 2006b) and DIN 1053-3:1990 (Deutsches Institut für Normung [DIN], 1990), there is no binding information for the design of complex structures using hollow blocks, which indicates that the issue of their strength has been little studied. The lack of sufficient experimental

and regulatory framework for the design of complex reinforced concrete structures utilising masonry from hollow blocks hinders the development of this field in construction.

According to the authors, paragraphs 3.6.1.2 (4) and 6.6.1 (4) of the EN 1996-1-1:2005+A1:2012 require adjustments.

Scientific research on the masonry work from hollow blocks is carried out in many countries, which confirms the relevance of the issue.

Studies and individual problems on the topic are presented in the works by Onishchik (1939), Matysek and Seruga (2005), Rudziński (2010), Drobiec (2016), Hasan, Saidi, Sarana and Bunyamin (2021), and Jafari (2021).

In the works by Popkow and Griniow (2006a, 2006b), the results of testing prisms made of hollow concrete blocks with different compositions of filling voids are presented. The masonry work from hollow blocks and the masonry work with concrete filling of different strengths and properties have been studied. Recommendations on the use of concrete filling are given, and the nature of the destruction is described.

In the work by Álvarez-Pérez, Chávez-Gómez, Terán-Torres, Mesa-Lavista and Balandrano-Vázquez (2020), mathematical models have been developed for calculating the compressive strength and elastic modulus of masonry prisms with hollow concrete blocks.

The works by Machado, Lübeck, Mohamad, Fonseca, and Barros da Silva Santos Neto (2019), and Syiemiong and Marthong (2020) study hollow concrete blocks of various configurations, with different mortar compositions in the joints, as well as examine how this affected the strength of the masonry.

In the works by Fahmy and Ghoneim (1995), Mohamad, Lourenc and Roman (2007), Jonaitis and Zavalis (2013), and Irnutan and Babota (2017), fragments of walls made of hollow concrete blocks of various configurations with and without concrete filling were tested, and the mechanism of wall destruction was studied.

In the work by Triwiyonoa, Nugrohoa, Firstyadia and Ottamaa (2015), fragments of walls made of hollow concrete blocks and strengthened with reinforced concrete were tested for out-of-plane bending. The ability to bend and the plasticity of the reinforced walls was increased by 5–16 times in relation to the non-reinforced walls.

The works by Pratyusha, Ashwin Thammiah, Aswath and Raghunath (2014), Bolhassani (2015), Calderón, Sandoval, Vargas and Araya-Letelier (2018), and Zhou, Du, Peng and Chen (2019) present the results of testing a fragment of a wall made of hollow concrete and ceramic blocks with separate sections of vertical and inclined reinforcement, where the voids of the masonry were filled with concrete of C20–C25 class.

In the work by Sandeep, Renukadevi, Manjunath and Somanath (2013), and Chi, Yang, Wang, Zhang and Quan (2019), the results of experimental studies and modelling of a wall fragment in the Ansys software with vertical reinforcement are presented. It is also possible to create prestressed masonry structures.

In the works by Thamboo (2018), and Thamboo, Zahra, Asad and Song (2021), the results of the analysis of calculations of reinforced masonry according to the Australian AS3700 (Standards Australia, 2018) and the British BS EN 1996-1-1:2005 (British Standards Institution [BSI], 2005b), BS 5628-2:2005 (BSI, 2005a) are presented.

The analysis of scientific works given above shows the insufficiency of research in the field of creating columns from concrete hollow blocks filled with reinforced concrete.

EXPERIMENTAL PROGRAM

Production of experimental columns

The experimental studies were carried out on specimens of columns with various reinforcement, as close as possible to the elements of full-scale structures in terms of cross-sectional dimensions, their reinforcement diagrams, and the composition of concrete.

Hollow concrete blocks from fine-grained concrete, made by vibropressing according to Besser technology, were used in all specimens of columns. A standard cement-sand mixture was used as a masonry mortar.

To prepare 1 m³ of concrete mix, a composition consisting of PC500 portland cement (300 kg), 5–10 crushed stones (1,040 kg), medium sand (780 kg), C3 plasticizer (2.34 kg) and water (165 kg) was used.

As a transverse reinforcement of the joints between the blocks, grids made of reinforcement Ø5 S500 were used. The longitudinal reinforcement used reinforcement rods Ø14, of various classes of steel: S500 and S800.

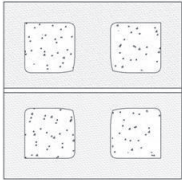
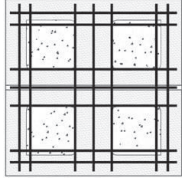
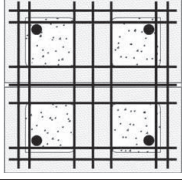
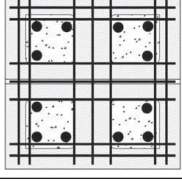
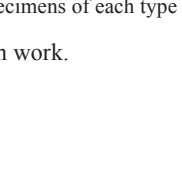
Table 1 shows the main characteristics of the materials used. Table 2 shows the types of specimen columns. In total, six types of columns were manufactured and tested, two identical specimens of each type.

Table 1. Characteristics of the materials, according to the test results of standard specimens

Average reduced prismatic strength of concrete		Joint solution strength	Longitudinal reinforcement rods			
			S500		S800	
blocks	fillings		yield strength	max. resistance	yield strength	max. resistance
MPa						
28.4	19.8	9.07	585	660	1 015	1 155

Source: own work.

Table 2. Characteristics of specimens

No	Cross-sections of specimens	Longitudinal reinforcement		Transverse reinforcement	Specimens
		steel grade	% of reinforcement		
1		–	–	–	k1
2		–	–	Welded mesh made of Ø5 S500 in each horizontal seam $\rho_{xy} = 0.39\%$	k2
3		S500	1.21		k3
4		S800	1.21		k4
5		S500	3.64		k5
6		S800	3.64		k6

Note: two specimens of each type have been manufactured and tested.

Source: own work.

The production of columns was carried out in the following order. The rods of the longitudinal reinforcement were fixed by manual electric arc welding to the lower steel plate. After concreting the lower head (Fig. 1a), two rows of blocks were laid out, with the installation of transverse reinforcement in horizontal seams and filling the voids with concrete. After finishing the masonry work, the formwork was installed, and the upper head was concreted (Fig. 1b), with the upper ends of the longitudinal reinforcement welded to the end plate.

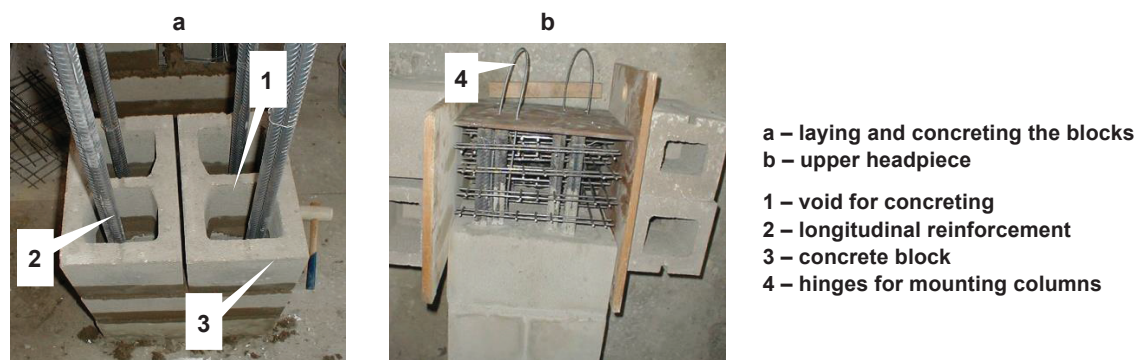


Fig. 1. Production of a specimen column

Source: own work.

Testing procedure

The specimens were loaded centrally, and the load transfer was carried out through pivotally mounted press plates.

The testing of columns after the concrete obtained strength in natural laboratory conditions was carried out at the age of at least 28 days in a PR-1000 hydraulic press.

Longitudinal strains were measured along each of the faces by means of dial indicators with a resolution of 0.01 mm fixed on a base of 600 mm. Mechanical strain gauges with a resolution of 0.001 mm and a base of 20 mm were used to measure the strains of the contact zone of the seam between the blocks. Additionally, dial indicators with a resolution of 0.002 mm and a base of 200 mm were fixed for measuring transverse strains on four faces. The reinforcement strains were measured on a base of 400 mm. The general view and the test scheme are presented in Figures 2 and 3. The cracking force was recorded on the scale of the press force gauge at the time of the formation of the first cracks. The crack opening width was measured at the level of the most stretched reinforcement using a reference microscope with an accuracy of 0.05 mm.



Fig. 2. General view of the testing of a specimen column

Source: own work.

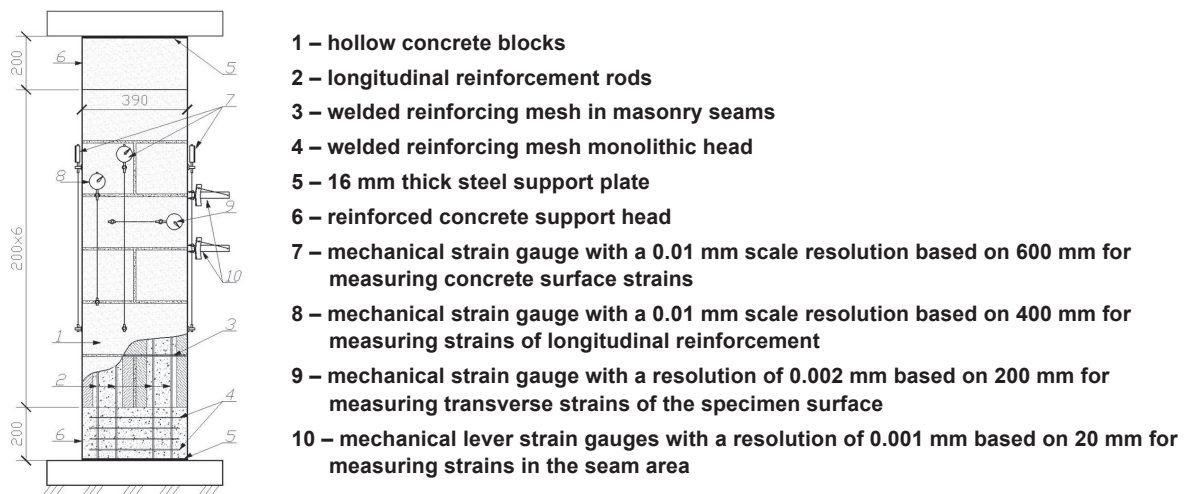


Fig. 3. The design of a specimen column with the placement of mechanical strain gauges

Source: own work.

The loading was carried out with a short-term mode of a stepwise increase in the load by 10% with the exposure at the level of each step for 12–15 min. In the steps preceding the exhaustion of the bearing capacity, the increase in the load was reduced to 5%. Readings from measuring instruments were recorded before and after the application of the load in consecutive stages. Measurements of the most important strain parameters were carried out before applying loads of the maximum load-bearing capacity of structures, as determined by the maximum reading of the control arrow of the press force meter.

RECOMMENDATIONS FOR THE CALCULATION OF COMPLEX COMPRESSED STRUCTURES

In the strain calculation model, the equilibrium condition for determining compressive strength is taken as:

$$\sigma_c(\varepsilon) \cdot A_c + \sigma_k(\varepsilon) \cdot A_k + \sigma_s(\varepsilon) \cdot A_s = N. \quad (1)$$

The first three terms are the forces from: concrete filling, concrete blocks, and reinforcement, respectively.

When compressing complex reinforced concrete elements at all stages of loading, all components are strained together:

$$\varepsilon = \varepsilon_k = \varepsilon_c = \varepsilon_s. \quad (2)$$

The condition (2) enables calculations of a complex compressed reinforced concrete element under the known strain laws of its components. To calculate the strength, we used the following analytical dependencies:

– for concrete (Hognestad, 1951):

$$\sigma_c(\varepsilon) = f_c \cdot \left[2 \cdot \left(\frac{\varepsilon}{\varepsilon_{cl}} \right) - \left(\frac{\varepsilon}{\varepsilon_{cl}} \right)^2 \right]; \quad (3)$$

– for masonry of hollow concrete blocks (Onishchik, 1939):

$$\sigma_k(\varepsilon) = \mu \cdot f_k \cdot [1 - e^{(-0.9 \cdot \varepsilon \cdot a)}]; \quad (4)$$

– for reinforcement:

$$\sigma_s(\varepsilon) = \varepsilon \cdot E_s. \quad (5)$$

Thus, the calculation is based on dependencies (3)–(5) that establish a relationship between stresses and strains: concrete, reinforcement, and masonry. The criterion for exhaustion of strength is the achievement of strains in the specimens, at which the total compressive force (concrete, blocks and reinforcement) reaches the maximum value.

Considering the above, it is proposed to calculate the strength of complex compressed reinforced concrete structures utilising hollow concrete blocks by using the dependence in the form of a formula:

$$N = A_{cmk} \cdot f_{cmk,eff} \cdot \left[2 \cdot \left(\frac{\varepsilon}{\varepsilon_{cmk,1,eff}} \right) - \left(\frac{\varepsilon}{\varepsilon_{cmk,1,eff}} \right)^2 \right] + \varepsilon \cdot E_s \cdot A_s, \quad (6)$$

$$\text{where } f_{cmk,eff} = f_{cmk} + \phi_0 \cdot \rho_{xy} \cdot f_{yd,xy}, \quad (7)$$

$$\text{where } f_{cmk} = \frac{f_k \cdot A_k \cdot \lambda_k + f_c \cdot A_c}{A_k + A_c}, \quad (8)$$

$$\text{where } \phi_0 = \frac{1}{0.23 + \psi}, \quad (9)$$

$$\text{where } \psi = \frac{\rho_{xy} \cdot f_{yd,xy}}{f_{cmk} + 10 \text{ MPa}}, \quad (10)$$

in which:

A_s – area of compressed reinforcement [mm² (in.²)],

A_c – area of compressed concrete filling [mm² (in.²)],

A_k – area of compressed masonry [mm² (in.²)],

A_{cmk} – area of concrete filling and masonry [mm² (in.²)],

ρ_{xy} – reinforcement of transverse reinforcement [%],

ε – longitudinal deformations of specimens [%],

ε_{c1} – longitudinal deformations of concrete at the peak point [%],

ε_k – longitudinal deformations of masonry [%],

ε_c – longitudinal deformations of concrete filling [%],

ε_s – longitudinal deformations of reinforcement [%],

σ_c – stresses in the concrete filling [MPa],

σ_k – stresses in the masonry [MPa],

σ_s – armature stresses [MPa],

N – total longitudinal compression force [kN],

f_c – characteristic compressive (cylinder) strength of concrete [MPa],

f_k – characteristic compressive strength of masonry [MPa],

$f_{yd,xy}$ – yield strength of the steel reinforcement grids [MPa],

f_{cmk} – reduced strength of the complex section [MPa],

$f_{cmk,eff}$ – reduced strength of the complex cross-section reinforced with transverse reinforcement [MPa],

λ_k – masonry utilisation factor ($\lambda_k = 0.80$),
 α – elastic characteristics of masonry ($\alpha = 780$),
 ψ, ϕ_0 – dimensionless coefficients.

RESULTS AND DISCUSSION

The specimens of columns without reinforcement (k1) were loaded until destruction, and the nature of the destruction was similar to that of conventional concrete prisms. Longitudinal cracks appeared at a load level of about 0.7–0.9 of the limit, along the entire height of the specimen, then the column was broken into separate vertical blocks. The destruction of centrally compressed specimens occurred in a brittle manner with the fragmentation of concrete.

The specimens of columns with transverse reinforcement (k2) were loaded until destruction. Longitudinal cracks occurred at a load level of 0.85–0.95 of the limit. The transverse grids limited the development of longitudinal cracks. The destruction of the specimen occurred due to the exhaustion of the bearing capacity of the concrete between the grids. The destruction occurs in a more plastic manner, compared to the specimen k1.

The destruction of the columns with S500 longitudinal reinforcement (k3, k5) proceeded smoothly, and longitudinal cracks appeared on the concrete surface around the longitudinal reinforcement. The destruction occurred with the loss of stability and buckling of the longitudinal reinforcement bars. The plane of the destruction, in most cases, was at an angle with a vertical axis of the order of 30–35° and usually coincided with previously formed longitudinal cracks. The buckling radius of the longitudinal reinforcement at the stage of destruction was small (90 mm). With a reinforcement of 1.21% (k3), buckling occurs on a segment limited by the transverse grids.

The initial stages of the destruction of the column specimens with S800 longitudinal high-strength reinforcement (k4, k6) was like the destruction of samples k3 and k5. The destruction occurred with the loss of stability and buckling of the longitudinal reinforcement bars. The plane of destruction, in most cases, was at an angle with a vertical axis of the order of 15–25° (i.e., during the destruction, almost all of the reinforcement was exposed). The radius of buckling of the longitudinal reinforcement at the stage of destruction was large (900 mm), and the reinforcement lost stability along the entire height of the specimen, bursting the grids with a scattering of concrete fragments.

The rods lost their stability within the middle section of the length of the structures and between the fixing points at their intersection with the transverse grids. The forms of bending are shown in Figure 4. The average strength of the columns is shown in Figure 5, while the destruction of the column specimens is shown in Figure 6.

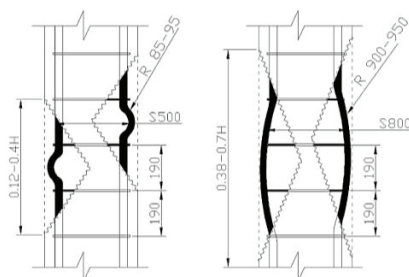


Fig. 4. Types of stability loss with longitudinal reinforcement of S500 and S800

Source: own work.

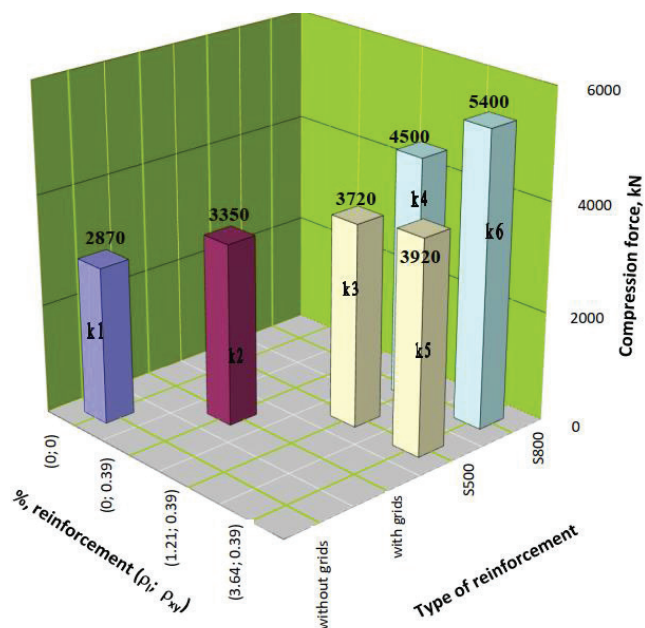


Fig. 5. Strength of specimens with different reinforcement

Source: own work.



Fig. 6. The nature of the destruction of the columns

Source: own work.

When comparing the results of the theoretical calculation of strength and the experimental data, satisfactory convergence was revealed (Table 3).

Table 3. Comparing the results

Sample	N_{Rd} [kN] (experimental data)	Using the formula (6)	
		N [kN]	N_{Rd}/N [kN]
k1	2 870	2 690	1.07
k2	3 350	3 300	1.02
k3	3 720	3 715	1.00
k4	3 920	3 865	1.01
k5	4 500	4 460	1.01
k6	5 400	5 305	1.02

Source: own work.

CONCLUSIONS

1. Transverse and longitudinal reinforcement of complex compressed reinforced concrete structures increases the levels of cracking. The destruction of a column begins with a decrease in its volume, then a subsequent increase due to the formation of microcracks and further destruction.
2. The analysis of experimental complex reinforced concrete structures with S800 high-strength reinforcement indicates the possibility of the full use of the mechanical properties of reinforcing steel.
3. To calculate the strength of complex compressed reinforced concrete structures, it is proposed to use dependence 6, which considers the descending branch of the strain diagram of concrete components and the processes of redistribution of forces in the presence of high-strength steel as part of the reinforcement section.
4. Based on the conducted experimental and numerical analysis, the authors of the article propose to change the wording of paragraphs 3.6.1.2 (4) and 6.6.1 (4) in the EN 1996-1-1:2005+A1:2012 “When a compression zone contains both masonry and concrete infill, the compressive strength should be calculated using a stress block based on the compressive strength of the weakest material” should be replaced with “When a compression zone contains both masonry and concrete infill, the compressive strength should be calculated proportionally for each material making up the total cross section”.

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NOŚNOŚĆ ŚCISKANYCH KONSTRUKCJI ZESPOLONYCH Z WYKORZYSTANIEM WIBROPRASOWANYCH PUSTAKÓW BETONOWYCH

STRESZCZENIE

Struktury, w których elementy z różnych materiałów współdziałają ze sobą, są z powodzeniem stosowane w różnych połączeniach. W ostatnich czasach pojawiły się nowe skuteczne materiały budowlane i produkty. W konstrukcjach zespolonych lub wieloskładnikowych elementy wykonane z materiałów o różnych właściwościach fizykochemicznych lub wytrzymałościowych należy rozsądnie łączyć w celu ich optymalnego współdziałania. Im pełniej wykorzystane są właściwości materiału komponentów, tym bardziej efektywna jest sama konstrukcja. Małe bloki betonowe stały się szeroko rozpowszechnione, co zaobserwowano dzięki analizie światowych doświadczeń. Zastosowanie muru z pustaków betonowych w nowoczesnym budownictwie różni się od tradycyjnego budownictwa tym, że powierzchnia pustki (do 70%) umożliwia tworzenie zespolonych konstrukcji nośnych o większej wytrzymałości poprzez wypełnienie ich monolitycznym betonem zbrojonym. Umożliwia to również przyspieszenie samego procesu budowlanego i obniżenie kosztów pracy na placu budowy. Celem pracy było zbadanie nośności centralnie ściśniętych słupów z pustaków z wypełnieniem żelbetonem, a także udoskonalenie metodologii obliczeniowej. Przeprowadzono badania eksperymentalne centralnie ściśniętych słupów o różnym procencie zbrojenia z wykorzystaniem pustaków jako szalunku stałego. W artykule przedstawiono wyniki badań wytrzymałości i nośności, nie uwzględniono w nim wyników badań odkształceń. Proponowana metoda obliczania zespolonych konstrukcji może być stosowana w praktyce projektowej. W trakcie badań zaobserwowano dobrą korelację między wynikami eksperymentalnymi a wynikami modelu analitycznego.

Słowa kluczowe: ściskanie betonu, słup żelbetonowy, pustaki betonowe

THE INFLUENCE OF EXCAVATION SUPPORT CONSTRUCTION ON THE SETTLEMENT OF ADJACENT STRUCTURES

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ABSTRACT

The paper presents an examination of the subsoil settlement in the neighbourhood of a deep excavation with particular reference to the excavation support construction method. Analysis was carried out for a selected deep excavation with a residential building in the vicinity. The most used technologies were considered, i.e., sheet pile walls, soldier pile walls, bored pile walls, and diaphragm walls. A total of 14 wall variants were examined to investigate the differences that certain characteristics have on the surrounding area. The impact of excavation support was assessed for two anchorage level schemes, taking into account three excavation phases. On this basis, the settlement profile next to the excavation wall was determined, and the settlement of the adjacent building was calculated. A key factor identified was the trench wall support scheme. Furthermore, a strong correlation was found between the stiffness of the wall and the maximum settlement observed.

Keywords: deep excavation, settlement, diaphragm wall, sheet pile wall, soldier pile wall, pile wall

INTRODUCTION

Due to the lack of available city space resulting from the continuous development of infrastructure, it is becoming increasingly common for newly designed buildings to have at least one underground storey and to be in the immediate vicinity of existing buildings. Each phase of the construction work is associated with the occurrence of different displacements (in magnitude and direction) and the time-varying displacements of the subsoil, and affect neighbouring buildings on a greater or smaller scale. One of the most relevant stages is a deep excavation phase with possible lowering of the groundwater table. The designer is required to prepare a project to support the excavation walls and to determine the influence of the construction execution on the adjacent area to ensure the safety of the excavation and the nearby facilities. As a result of the excavation, extensive wall displacements may occur and cause considerable settlement at the foundation level of the neighbouring structures. This situation may threaten the stability of all the facilities or “only” affect the utility conditions (Korff, 2009; Pająk, Sękowski, Kwiecień & Wieczorek, 2018). Settlement of the structure, depending on its location and the ground surface deformation, may be uniform or non-uniform, with the latter posing a greater negative influence. The issue of predicting ground deformation around an excavation and the influence on neighbouring buildings is an important issue in engineering practice and

has been studied by many researchers in various aspects (Hsieh & Ou, 1998; Horodecki & Dembicki, 2007; Popielski, 2012; Mitew-Czajewska, 2014; Mei, Wang, Zhou & Fu, 2022).

The range and magnitude of settlement taking place are influenced by many factors. The most important are the depth of the excavation, the type of soil, the static scheme in which the retaining structure operates, and the support technology. The settlement profile in the vicinity of the excavation depends on the magnitude and nature of the deflection of the wall. It is not possible to completely avoid the shoring displacement; however, an excessive horizontal displacement of the excavation wall, identified as greater than 3% of the excavation depth (H), must not be allowed. According to Long (2001), the main factor (33%) for excessive displacements is the initial phase of the structure, i.e., when the wall is working in a cantilevered pattern. The second most commonly identified cause was the use of flexible support technology (22%).

The influence range of an excavation is usually defined as a multiple of the excavation depth (H). Various authors have defined, based on empirical data, the predicted influence range as follows: O'Rourke and Clough (1990) established it as $2-4H$ for cohesive soils (London clays), and for non-cohesive soils, Schweiger, Freiseder and Breymann (1999) found this range to be $1.5-2H$. In Poland, the most widely used guidelines in practice are those published by Kotlicki, Łukasik, Godlewski and Bogusz (2020). The authors suggest assuming a range equal to $2H$ in sands, $2.5H$ in silts, and $3.0-4.0H$ in clays. Distance can be reduced by 20% if the groundwater level is not lowered. According to these guidelines, the area with the greatest influence is determined as $0.5H$ in sands, $0.75H$ in silts and $1H$ in clays. The maximum vertical displacements in the vicinity of the excavation are estimated to be between $0.002H$ in compacted sands and $0.02H$ in cohesive soils (Michalak & Przybysz, 2021).

The study focused on analyses of the static scheme influence and the type of excavation wall on the settlement of the adjacent area and the residential building in the vicinity. The assessment was based on a case study with two anchorage level schemes considering the three stages of excavation. The effect of the selection wall profile was also analysed with respect to the different types of walls: rigid (bored pile wall, diaphragm wall) and flexible (sheet pile wall, soldier pile wall). A total of 14 different variants were analysed for each scheme and stage. As a result, the influence of these elements on the range, magnitude, and profile of the ground surface settlement was assessed.

MATERIAL AND METHODS

The location on Kollątaja in Wrocław (Poland) was used for analyses. A seven-metre-deep excavation was designed adjacent to the existing building, as shown in Figure 1a. The excavation segment (blue line) that has been examined is located close to the existing building and, therefore, will have the greatest influence on the neighbourhood. Figure 1b shows a side view of the actual five-storey townhouse in the vicinity of the planned excavation. The geotechnical profile and soil parameters were adopted based on local geological data and are summarised in Table 1. The soil profile is mainly composed of compacted medium sands, and the groundwater table has not been identified.

The total height of the wall was assumed to be 11 m. The location and loads from the adjacent property were set as follows. The first floor is elevated and intended for commercial premises. It has been assumed, in a simplified manner, that all storeys above the service units are of identical height and intended as residential units. Due to the lack of documentation of the foundation, a three-strip footing, one metre wide (pink lines in Fig. 1a), spaced 6 m apart was assumed. Subsequent footings, due to the large distance, were omitted. The axis of the closest footing was taken at 3 m from the retaining structure and at a depth of 0.8 m. The design loads (q) on the individual footings were assumed from the estimated construction load calculations as 417.75 kPa (for the footing F1) and 477.63 kPa (for F2 and F3). The calculation schemes are shown in Figure 2. To assess the influence of the support scheme and the phasing of the work, two schemes differing in the location of

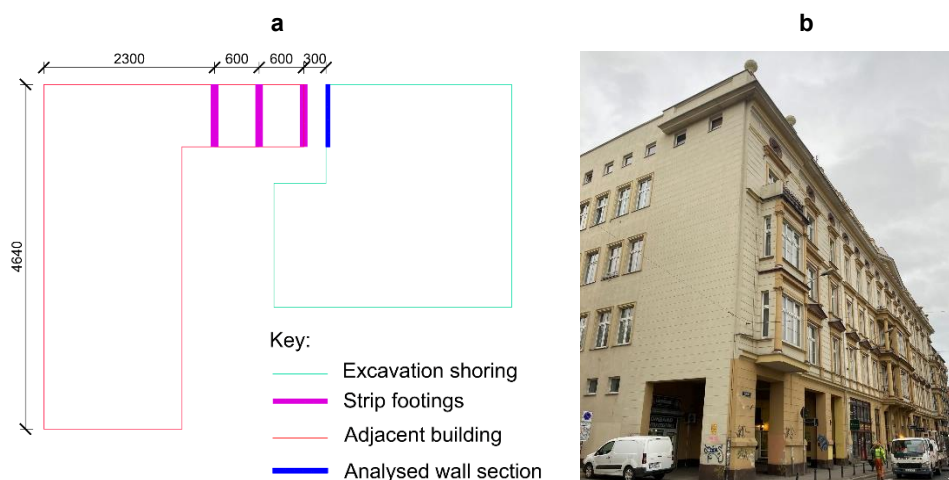


Fig. 1. Scheme of the deep excavation (a) and the townhouse in the vicinity (b)

Source: own work.

Table 1. Soil parameters

No	Soil	I_C [-]	I_D [-]	γ [kN·m ⁻³]	c [kPa]	φ [°]	ν [-]
1	sand with clay	0.60	–	20.60	10.65	11.6	0.32
2	medium sand	–	0.45	16.68	0	32.7	0.25
3	medium sand	–	0.70	17.66	0	34.2	0.25
4	medium sand/fine sand	–	0.80	17.66	0	34.9	0.25
5	clay with gravel	0.60	–	19.50	10	26.0	0.35

Source: own work.

the ground anchor heads were considered, and for each scheme, three stages of excavation were examined. Ground anchors with a 2 m spacing and with a pre-tension of 350 kN (upper) and 400 kN (lower) were used as support for the excavation wall in Scheme 1. In Scheme 2, it was 300 kN and 400 kN, respectively. The inclination, the total length, and the bond length in both variants were the same.

First, a static analysis was carried out to determine internal forces. Next, different excavation wall variants that met the ultimate limit state conditions were selected to analyse the wall and surface displacement. Two types of flexible wall (sheet and soldier pile wall) and two types of rigid wall (pile and diaphragm wall) were selected. Each technology was modelled in two or more common variants to test the differences that each parameter may have on the settlement of the subsoil next to the excavation. Due to the different positions of the ground anchor heads in Schemes 1 and 2, there was a difference in the internal forces. In both cases, the optimum profiles and reinforcement were selected in terms of the bending moment capacity. The exceptions are Variants A2 and A4 – due to the lack of profiles with smaller cross-sections – the same profiles are used in Schemes 1 and 2. The parameters of the retaining structures are shown in Table 2. The stiffness of the wall per metre is taken as EI , where E is Young's modulus of the material and I is the moment of inertia of the profile. In all cases, C30/37 concrete and S235 steel were used.

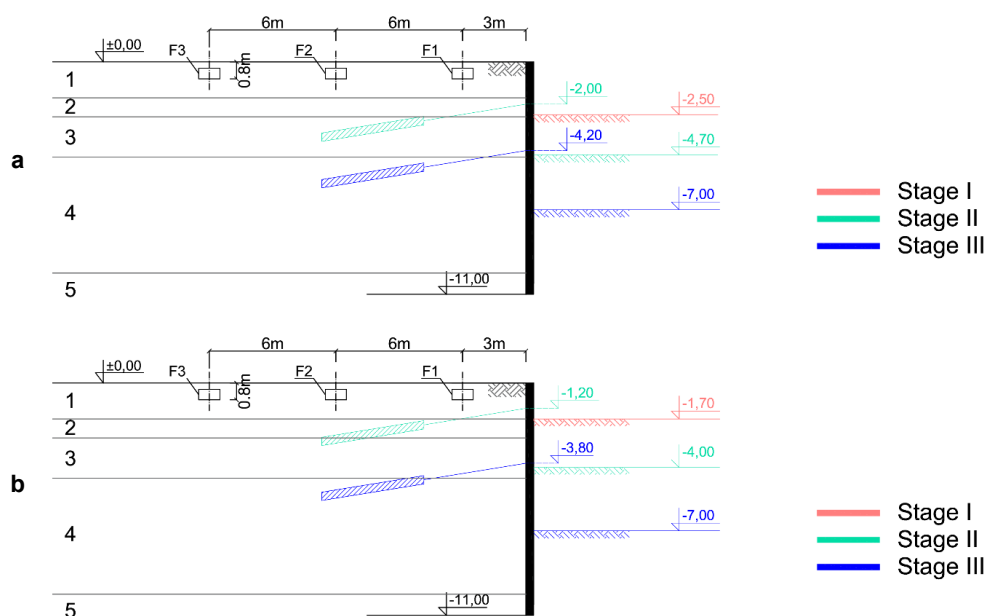


Fig. 2. Task Scheme 1 (a) and Scheme 2 (b)

Source: own work.

Table 2. The list of types and technical parameters of excavation walls

No	Type	Scheme 1		Scheme 2	
		description	EI [kNm ²]	description	EI [kNm ²]
A1	sheet pile wall ^c	“Z” profile MMZ11-1	30 030	“Z” profile SCZ 14	20 601
A2	sheet pile wall ^h	“Z” profile AZ 12-700	39 690	“Z” profile AZ 12-700	39 690
A3	sheet pile wall ^c	“U” profile MMU11-1	46 620	“U” profile MMU7-1	21 630
A4	sheet pile wall ^h	“U” profile PU 400×125	35 280	“U” profile PU 400×125	35 280
B1	soldier pile wall	HD260×68.2 1 m spacing	22 050	HE240 AA 1 m spacing	12 264
B2	soldier pile wall	HP305×79 1 m spacing	34 440	HD260×68.2 1 m spacing	22 050
C1a	bored pile wall ^s	0.6 m diameter 0.5 m spacing IPE180 per pile	210 870	0.4 m diameter 0.3 m spacing IPE A 120 per pile	61 200
C1b	bored pile wall ^s	0.6 m diameter 0.5 m spacing 7 Ø14 bars per pile	412 500	0.4 m diameter 0.3 m spacing 6 Ø10 bars per pile	119 100
C2a	bored pile wall ⁱ	0.6 m diameter 0.6 m spacing IPE200 per pile	181 170	0.4 m diameter 0.4 m spacing IPE140 per pile	49 800

Table 2 (cont.)

No	Type	Scheme 1		Scheme 2	
		description	EI [kNm ²]	description	EI [kNm ²]
C2b	bored pile wall ^t	0.6 m diameter 0.6 m spacing 6 Ø16 bars per pile	349 800	0.4 m diameter 0.4 m spacing 6 Ø12 bars per pile	94 200
C3a	bored pile wall ^{cn}	0.6 m diameter 0.8 m spacing IPE240 per pile	140 580	0.4 m diameter 0.6 m spacing IPE200 per pile	37 800
C3b	bored pile wall ^{cn}	0.6 m diameter 0.8 m spacing 8 Ø16 per pile	262 350	0.4 m diameter 0.6 m spacing 12 Ø10 per pile	62 700
D1	diaphragm wall	0.4 m thickness 5 Ø20 per metre	175 890	0.4 m thickness 10 Ø10 per metre	159 900
D2	diaphragm wall	0.6 m thickness 5 Ø16 per metre	594 000	0.6 m thickness 10 Ø10 per metre	540 000

^ccold rolled; ^hhot rolled; ^ssecant; ^ttangent; ^{cn}contiguous.

Source: own work.

On this basis, the influence range of the excavation on settlement and their magnitude was assessed for all the cases examined. All analyses were carried out according to Eurocode 7 (European Committee for Standardization [CEN], 2004) using the method of dependent pressures with GEO5 software – Sheeting Check. In the ultimate limit state, the DA2 was used, and in the serviceability limit state of the neighbouring townhouse, four parameters were assessed: settlement, rotation, relative deflection, and tilt of the building.

RESULTS AND DISCUSSION

When the ultimate limit state of the excavation support is analysed, the bending moment assessment is crucial. By carefully selecting the static support scheme, its magnitude can be minimised. It should be emphasised that not only the final scheme of the structure's operation, but also all intermediate stages must be considered. The values of the maximum bending moments for the different excavation stages in Schemes 1 and 2 (see Fig. 2) are summarised in Table 3. In Scheme 1, the highest values of the bending moment are observed in the first stage, i.e., in the cantilever pattern. In Scheme 2, the highest bending moment was reached at the final stage, but in all stages of the structure's operation, the values were quite similar.

The values of vertical deformation of the ground surface near the excavation wall calculated for all schemes, stages, and variants of the excavation wall are shown in Figures 3 and 4. The predicted theoretical influence range, according to Kotlicki et al. (2020), is 11.2 m (due to the lack of lowering of the water table), and the expected zone of greatest influence is 3.5 m. The total calculated influence range of the excavation in both schemes is 10.56 m (about 1.5*H*), which is slightly lower. However, in this respect, the results are in line with the dataset for sands. Regarding the zone of greater influence, in the case of Scheme 1, the maximum settlement occurs up to approximately 4 m from the excavation wall, but beyond this distance, the excavation influence and the ground surface settlement continue to be significant. In Scheme 2, the maximum settlement is found in the distance up to 5 m from the excavation wall. As a result, it should be noted that in the zone considered to be less affected by the excavation, this influence may still be high.

Table 3. The values of maximum bending moments

Scheme	Moment [kNm]		
	Stage I	Stage II	Stage III
1	174.75	111.72	81.85
2	63.91	69.50	73.20

Source: own work.

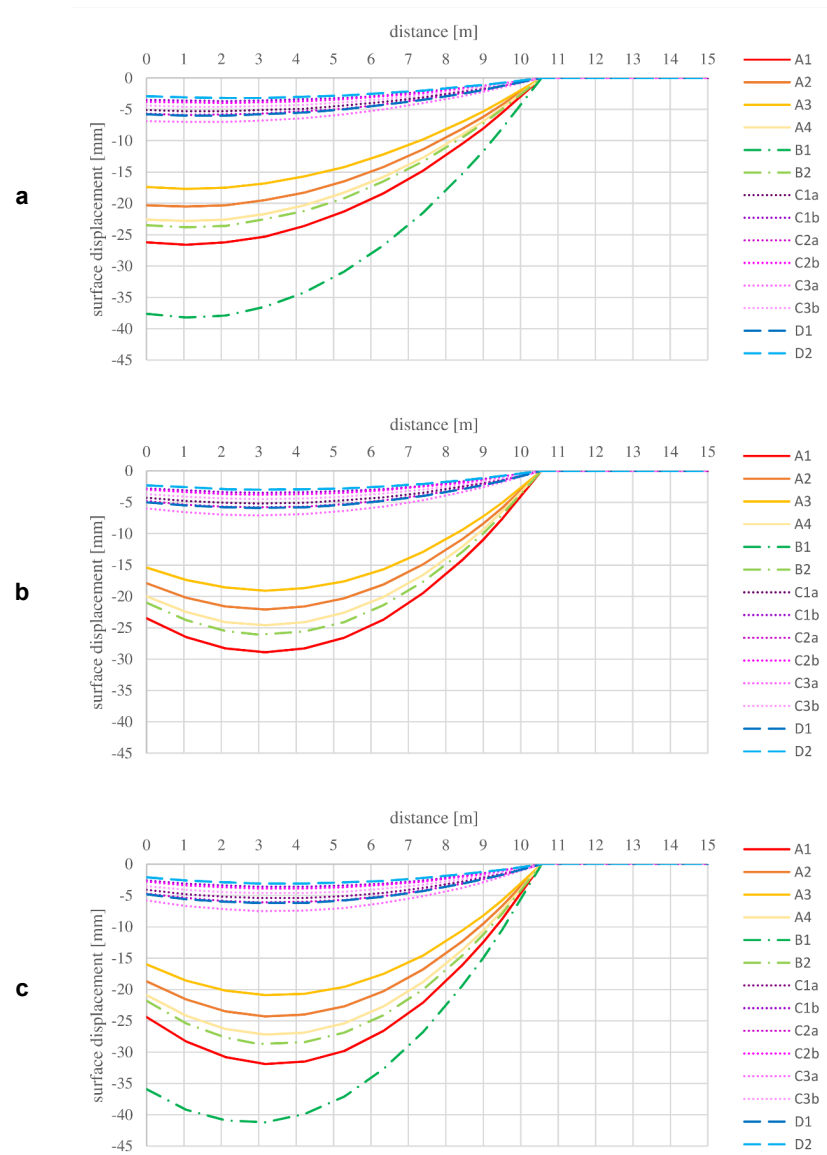


Fig. 3. The summary of vertical deformation of the ground surface depending on the distance from the excavation in Stage I (a), Stage II (b) and Stage III (c) for Scheme 1

Source: own work.

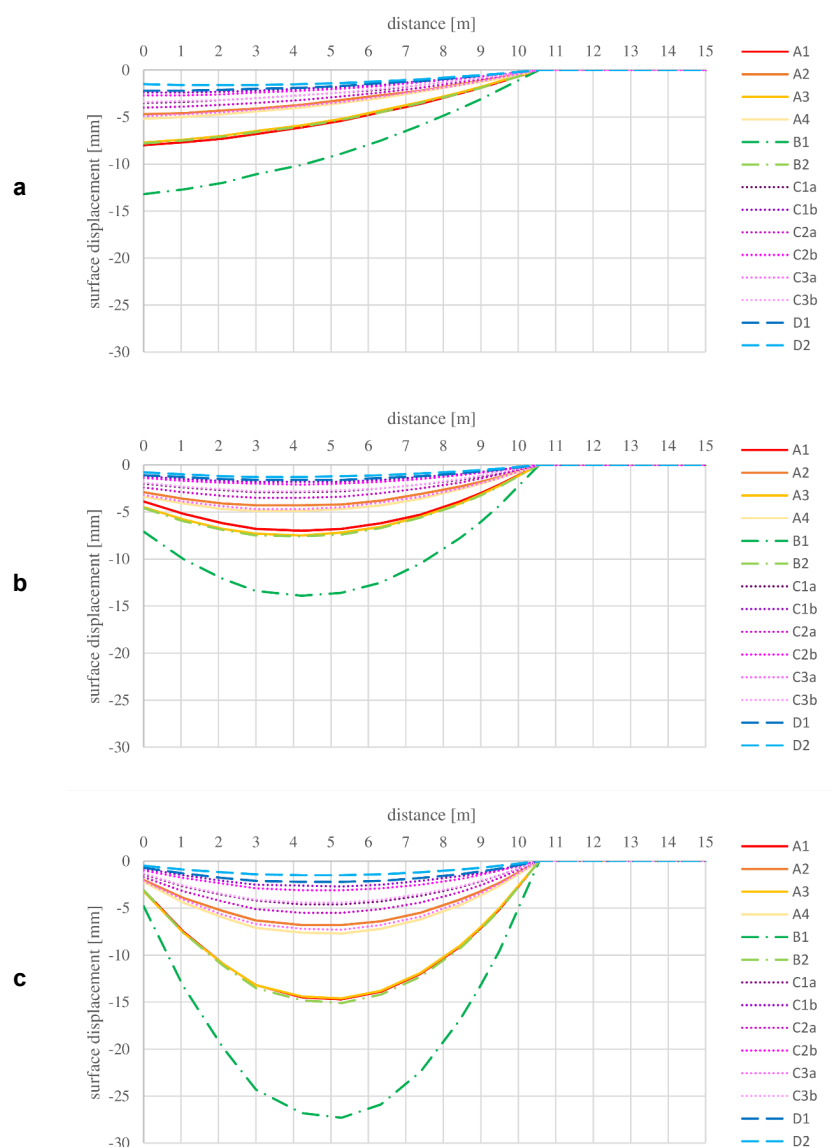


Fig. 4. The summary of vertical deformation of the ground surface depending on the distance from the excavation in Stage I (a), Stage II (b) and Stage III (c) for Scheme 2

Source: own work.

Significant differences can be observed when comparing the settlement profile in Schemes 1 and 2. In Scheme 1, the largest increase in maximum deformation occurs in Stage I (where the largest bending moments were observed). The increases in subsequent stages are small, and for some of the schemes, i.e., rigid walls (excluding the C3a pile wall) and Variant B1 (soldier pile wall), even a reduction of settlement was observed in Stage II. The observed pattern was the result of the horizontal deformation of the wall itself, for which the highest values occurred at the top of the wall in Stage I. In contrast, in Scheme 2, in Stage II, a reduction of settlement was observed too (except for Variant B1), but in Stage III, a large increase of vertical

displacements in relation to Stage I was recorded. In addition, generally, the settlement found for Scheme 2 is considerably less. The maximum horizontal deformation of the wall in this case also occurred mostly at the top of the wall in Stage I (but was much lower) or, for walls with the lowest stiffness, below the lower anchor head in Stage III. Thus, the significant influence of the applied anchorage level scheme and the staging of the works on the settlement of the subsoil can be seen. The shallow support location of the excavation wall (by ground anchors or bracing) has a beneficial effect not only on the bending moments but, above all, on the settlement of the surface next to the trench. This is because the depth of the excavation during the cantilevered stage, described as the most dangerous operation pattern, is reduced. The position of the anchorage also determines the nature of the wall deflection and settlement profile. In the case of Scheme 1, where the anchors are installed lower, the greater displacements are located closer to the wall than in Scheme 2.

Special attention should be paid to Variant B1 in Scheme 1. As mentioned above, a reduction in settlement was observed in Stage II. For Variant B1, they have not only decreased, but also ground uplift was observed near the excavation. This was omitted in Figure 3 for readability reasons and is shown separately in Figure 5. This is the wall with the least stiffness in this scheme, and the observed effect is due to the pre-tension of the ground anchor used. However, Scheme 2 uses a wall with lower stiffness, and this effect did not occur. It should be noted that with ground anchors and a wall of very low stiffness, uplift of the ground next to the wall may theoretically occur. This should be monitored through the choice of excavation support scheme and pre-tension of the anchors.

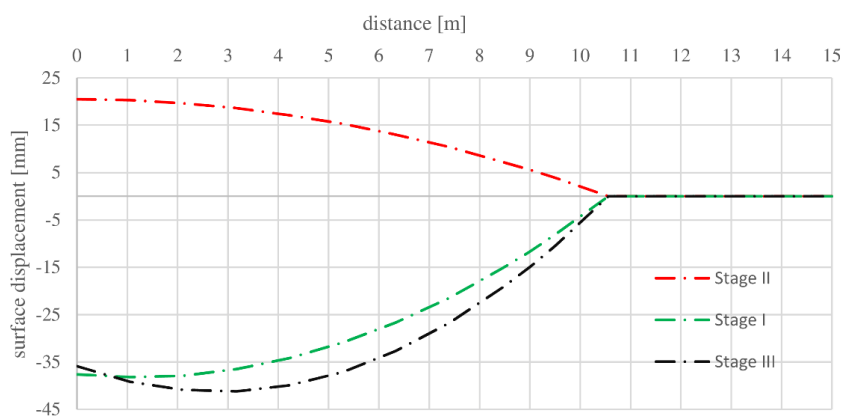


Fig. 5. The summary of vertical deformation of the ground surface for the B1 type of excavation wall for Scheme 1

Source: own work.

Analysing the effect of the selection of excavation wall technology, as expected, it was confirmed that the wall identified as being rigid (Variants C and D) generally gives less ground surface settlement next to the excavation than flexible ones (Variants A and B). The stiffness of the excavation wall expressed as EI was identified as the main factor. Overall, it can be considered that the most important parameter affecting stiffness is the choice of steel profile or reinforcement. Even within a single technology, it is possible to choose a variant with significantly different stiffnesses. The maximum surface displacements after complete excavation (Stage III) as a function of the excavation wall stiffness is shown in Figure 6. As can be seen in both schemes, maximum settlement is a power function of the wall stiffness (EI). Stiffness in the range up to 100 kNm^2 has the greatest influence on settlement, and for higher values, the influence of stiffness is low. Therefore, it can be concluded that it is ineffective to increase the stiffness of the wall to achieve less

settlement in a certain stiffness range. Of greater importance is the use of an accurate static scheme and wall support levels. Considering the influence of the selection of the technology variant, it can be observed that the greatest differences in settlement occur for flexible walls (Variants A and B), which is obviously related to the influence of their stiffness. However, when a particular static scheme is selected, even technologies considered to be rigid (Variants C and D) can produce significantly different settlement results. The reason for this is that walls with relatively low stiffness (less than 100 kNm²) are sufficient to transmit the bending moments.

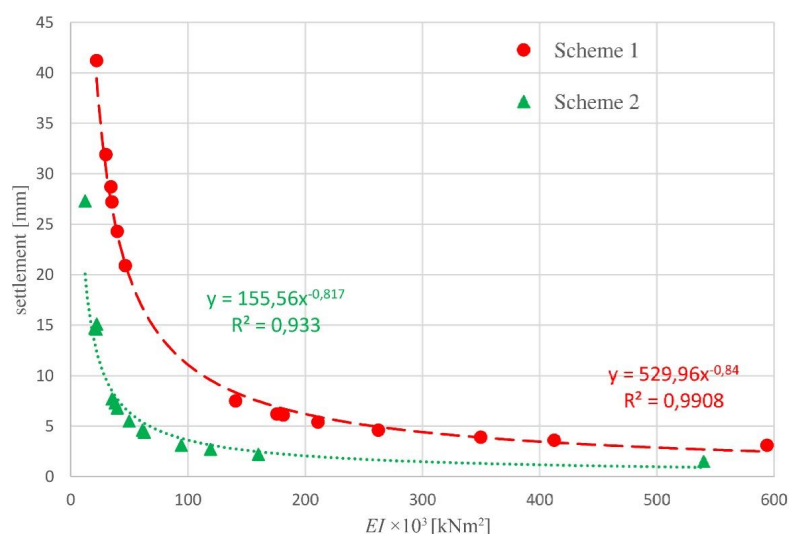


Fig. 6. Relation between the stiffness of the type of excavation wall (EI) and maximum ground settlement behind the excavation wall for Scheme 1 (red) and Scheme 2 (green)

Source: own work.

For all variants analysed, the maximum ground surface settlement (from Stage III) obtained for rigid technologies was between 3.1 mm and 7.5 mm in Scheme 1 and between 1.5 mm and 7.3 mm in Scheme 2. It is about from $0.0002H$ to $0.001H$. For flexible technologies, it was between 20.9 mm and 41.2 mm in Scheme 1 ($0.003H$ – $0.006H$) and between 14.6 mm and 27.3 mm in Scheme 2 ($0.002H$ – $0.004H$). Thus, the use of an alternative variant and an adequate support scheme can reduce the predicted displacements several times. The values for rigid and some flexible solutions are in line with the data in the literature, but, in general, the use of flexible walls can lead to higher settlement than initially assumed. Therefore, special care must be taken when using this type of technology. As can be seen, the selection of the optimum protection method to limit settlement should take several aspects.

Analysing the effect of subsoil displacement on the adjacent building, similar conclusions can be reached. Here, however, the key element is the settlement of the foundations and its influence on the construction. Table 4 presents the final values of maximum settlement $s_{\max}$, relative deflection $\Delta_{\max}$, rotation $\theta_{\max}$, and tilt $\omega_{\max}$ calculated based on F1, F2 and F3 footing vertical displacements. The limits have been adopted in accordance with the National Annex of Eurocode 7 as 50 mm, 10 mm, 0.002, and 0.003, respectively. Bold indicates where the limit state for the parameter is exceeded. With this location of the footings, there is a clear tilt of the building towards the excavation.

Table 4. The summary of settlement in Stage III

No	Scheme 1				Scheme 2			
	$s_{\max}$ [mm]	$\Delta_{\max}$ [mm]	$\theta_{\max}$ [-]	$\omega_{\max}$ [-]	$s_{\max}$ [mm]	$\Delta_{\max}$ [mm]	$\theta_{\max}$ [-]	$\omega_{\max}$ [-]
A1	31.9	3.5	0.0032	0.0027	13.2	0.5	0.0012	0.0011
A2	24.3	2.7	0.0025	0.0020	6.3	0.0	0.0005	0.0005
A3	20.9	2.3	0.0021	0.0017	13.2	0.4	0.0012	0.0011
A4	27.2	3.0	0.0028	0.0023	7.1	0.1	0.0006	0.0006
B1	41.2	5.7	0.0044	0.0034	24.3	1.1	0.0022	0.0020
B2	28.7	3.1	0.0029	0.0024	13.5	0.5	0.0012	0.0011
C1a	5.4	0.6	0.0005	0.0005	4.2	0.0	0.0004	0.0004
C1b	3.6	0.4	0.0004	0.0003	2.5	0.0	0.0002	0.0002
C2a	6.1	0.7	0.0006	0.0005	5.1	0.0	0.0004	0.0004
C2b	3.9	0.4	0.0004	0.0003	2.9	0.0	0.0002	0.0006
C3a	7.5	0.9	0.0008	0.0006	6.7	0.1	0.0006	0.0006
C3b	4.6	0.5	0.0005	0.0004	4.1	0.1	0.0004	0.0003
D1	6.2	0.7	0.0006	0.0005	2.1	0.1	0.0002	0.0002
D2	3.1	0.5	0.0003	0.0003	1.4	0.0	0.0001	0.0001

Source: own work.

However, the most important factor in this case is the rotation. In Scheme 1, in all flexible wall variants (A and B), the serviceability limit state conditions were exceeded. For rigid ones (C and D), all conditions are met. On the contrary, for Scheme 2, the conditions were met for almost all wall types (except for soldier pile wall B1). This indicates that, with the right choice of support levels, even technology considered flexible can be sufficient to ensure serviceability conditions for neighbouring structures. Obviously, the settlement values would be different with a different footing location.

CONCLUSIONS

The selection of the most effective protection of a deep excavation wall for settlement limitation should consider several aspects, and each case should be analysed individually. The extensive case study presented confirmed the well-known dependence of settlement on the type of trench wall construction. However, some additional findings can be drawn from the results presented. The outcomes can be summarised as follows:

- The position of the head of the ground anchors and the staging of the excavation, i.e., the working pattern of the structure, are key factors affecting the maximum bending moments and the value of settlement and the subsoil settlement profile; positioning the upper anchorage level higher reduces the height of the wall in the cantilever stage and limits surface settlement, but moves the location of the point of maximum settlement further away from the excavation.
- The total influence range of the excavation for the analysed schemes is consistent with the literature data for sands, but the range of the greatest excavation influence on ground surface settlement was larger than expected regardless of the support scheme used; therefore, significant settlement is to be expected even away from the zone of direct influence of the excavation.

- The settlement occurring when using flexible walls (such as soldier pile walls or sheet pile walls) is generally greater than those for bored pile or diaphragm walls (rigid solutions), but application of adequate technology variants can reduce the settlement even for profiles with relatively low stiffness; however, special care must be taken when using low stiffness solutions, as settlement may be greater than indicated in the literature.
- The major parameter influencing settlement around an excavation is the stiffness of the excavation support wall used, with this influence being greatest at a stiffness (EI) of up to 100 kNm² per metre – at higher stiffnesses, the reduction in settlement is insignificant; thus, for flexible walls (and to some extent rigid walls), the main factor to consider should be the stiffness of the section and not other parameters.
- The serviceability limit state analysis of the structure adjacent to the excavation indicated that limit values were exceeded almost only for the rotation parameter and the flexible walls; however, even walls with low stiffness can be sufficient with an appropriate excavation support scheme.

Authors' contributions

Conceptualisation: M.M.; methodology: M.M. and M.T.; validation: M.M. and M.T.; formal analysis: M.M. and M.T.; investigation: M.M.; resources: M.M.; data curation: M.M.; writing – original draft preparation: M.T.; writing – review and editing: M.M. and M.T.; visualisation: M.M. and M.T.; supervision: M.T.; project administration: M.T.; funding acquisition: M.T.

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

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WPLYW KONSTRUKCJI OBUDOWY WYKOPU NA OSIADANIA ZABUDOWY SĄSIADUJĄCEJ

STRESZCZENIE

W pracy przedstawiono badanie osiadania podłoża gruntowego w sąsiedztwie głębokiego wykopu ze szczególnym uwzględnieniem metody zabezpieczenia ścian wykopu. Analizę przeprowadzono dla wybranego głębokiego wykopu, w sąsiedztwie którego znajduje się budynek mieszkalny. Rozważono najczęściej stosowane technologie, tj. ściankę szczelną, ściankę berlińską, palisadę oraz ścianę szczelinową. Łącznie przeanalizowano 14 wariantów obudowy, aby zbadać, jakie właściwości mają wpływ na otaczający ją obszar. Wpływ podparcia wykopu oceniono dla dwóch schematów poziomów zakotwienia z uwzględnieniem trzech faz wykopu. Na tej podstawie określono profil osiadania obok wykopu i obliczono osiadania sąsiedniego budynku. Zidentyfikowanym kluczowym czynnikiem był schemat podparcia ścian wykopu. Ponadto stwierdzono silną korelację między sztywnością obudowy a zaobserwowanymi maksymalnymi wartościami osiadania.

Słowa kluczowe: głęboki wykop, osiadanie, ściana szczelinowa, ścianka szczelna, ścianka berlińska, palisada

VISUALISATION IN ARCHITECTURE – OPPORTUNITIES AND THREATS

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ABSTRACT

The development of computer technology, the computing power of graphics cards and processors, and the use of appropriate software allows us to create extremely realistic three-dimensional images. The effects of the generated visualisations can be difficult to distinguish from real photos of objects. Architects often verify the fulfilment of design goals based on a rendered digital image. Unfortunately, designers are often not fully aware of the limitations and simplifications of the tools used to create these visualisations. An uncritical approach to the presented results may lead to various design errors. This article presents the possibilities of visualisation in selected computer programs used by architects, and cases in which correct visualisation is possible only through the use of specialised software. The article also pays special attention to the possibility of errors in the visualisation of architectural lighting.

Keywords: architecture, 3D visualisation, Photopia, architectural lighting, visualisation in architecture

INTRODUCTION

Three-dimensional visualisation has a vast future ahead of it, and it is continuously evolving. This is particularly evident in the fields of architecture and interior design. The graphic and simulation capabilities of computers are already significantly influencing the way houses are built, the design and production process, error elimination, and, of course, the overall project completion time. The development of collaborative digital platforms allows for the exchange of ideas and data, enabling designers from related disciplines to engage in shared and efficient engineering (Glinko, 2022). This article presents various possibilities for creating 3D visualisations, focusing on the capabilities and limitations associated with visualisation in architectural lighting. Visualisation can significantly reduce the costs and time spent on field testing with numerous illuminators, as well as the analysis of lighting solution variants and concepts.

In such applications, visualisation serves as a crucial element in confirming the correctness of the design concept. Creating accurate visualisations requires an understanding of the limitations and capabilities of the employed 3D visualisation software. These limitations may arise, for example, from the construction of the light source model or the definition of the optical properties of the materials. Architectural software introduces certain simplifications that can lead to significant errors in some cases. In this regard, it is necessary to use specialised software for designing optical systems, such as Photopia. Fortunately, software manufacturers increasingly allow the utilisation of these specialised tools within familiar architectural software platforms,

like Rhino or SolidWorks. This not only enables designers to work in a familiar environment but also facilitates the creation of highly accurate visualisations in atypical lighting situations. Examples of the need for specialised tools include simulating the light distribution below the photometric measurement threshold distance or mixing colours of light from sources with different colour temperatures. Additionally, designers can benefit from the built-in parametric design functions of the software, enabling them to create unique and individual shapes. An example of this is the integration of Photopia with Rhino software.

VISUALISATION IN ARCHITECTURE

Three-dimensional visualisation is the process by which graphic content is created using 3D software. Such terms like 3D rendering, computer generated imagery (CGI), and 3D graphics are associated with the concept of visualisation. In recent years, 3D visualisation technology has been implemented in many industries to present high-quality graphic content, influencing better communication, increasingly real digital experiences and the visual verification of proposed design solutions.

The main industries associated with visualisation techniques include:

- product design, manufacturing and presentation,
- architecture and interior design,
- media and entertainment.

Architecture uses various visualisation methods, while designers use both 2D visualisation and spatial visualisation. Spatial visualisation makes it possible to depict the designer's work much more accurately, while three-dimensional visualisation is becoming an indispensable part of architectural designs. At the same time, the forms of spatial visualisation are evolving from static to dynamic visualisation, while a relatively new trend is interactive visualisation.

Static visualisation methods make it possible to present a project from the specific perspectives chosen by the designer. An example of a simple static visualisation is shown in Figure 1, a visualisation of one of Warsaw's housing estates.

Dynamic visualisation, or animation, makes it easier to understand the spatial relationships between the designed objects. Often, in addition to the image itself, designers add an audio background. Interactive visualisations allow the use of modern design presentation techniques, such as a virtual walk-through. The client can decide on his own in which direction they wish to move and from what perspective to observe the digital reality. In summary, 3D visualisation is a form of graphical representation of reality, which allows you to become acquainted with the object at any stage of its design. In this way, visualisation provides a platform for communication with the client, which allows verification of the design assumptions during the design process. The aspects presented in the visualisation may concern both technical and aesthetic matters. Modern software can combine visualisation techniques along with simulation tools, while also monitoring the design process and alerting us to the emergence of certain design risks and constraints. The following examples illustrate the possibilities of supporting the designer in the process of realising 3D visualisations in selected CAD programs.

Specialised computer programs make it possible to create a virtual model of an object from a photo. Creating a spatial object from a photo, with manual modelling, is typically a rather time-consuming process; however, volumetric design software is able to use appropriate algorithms to generate the 3D models while also continuing to strongly increase the development process.

These involve not only simple buildings, but also faces and figures. Visualisation software may also include photogrammetry software, which allows the creation of 3D models from a series of 2D images or photos taken from different angles. Figure 2 shows the process of creating a 3D model of a tenement house on Wąski Dunaj

in Warsaw's Old Town, using a previously taken photograph. The spatial model of the tenement was created using SketchUp software, while the reproduction was achieved through manual modelling technique using the photo matching function.



Fig. 1. Static visualisation of a housing estate in Warsaw

Source: own work.



Fig. 2. Illustration of the process of creating a three-dimensional model of a tenement house from a photo. The tenement house is located in the Old Town of Warsaw. SketchUp software was used to create the building model, while the digital model was made using a hand modelling technique

Source: own work.

Light and its reaction with materials play a key role in the correctness of the visualisation of spatial effects. The degree of realism of the perception of the modelled objects, therefore, depends on the correctly defined optical properties of the materials and properly created models of the light sources. Often, when it is necessary to obtain real illumination distributions on illuminated surfaces, architectural software may be insufficient. Correct visualisation requires the use of additional specialised simulation tools. On the software market there is currently a trend to transfer the capabilities of specialised programs to architectural or engineering software

in the form of plug-ins. One example of this is Photopia software from an American company, LTI Optics. This company specialises in software for simulating light distribution and supporting designers in modelling such optical systems as reflectors, lenses, prisms, scattering glasses, etc. Due to the interdisciplinary nature of many engineering disciplines, they decided to implement its software into Rhino and SolidWorks. This new approach to software implementation methods increased not only the simulation capabilities of the software for which the plug-ins were prepared, but also of Photopia itself. An additional advantage is the ability of designers to work in a familiar software environment (LTI Optics, 2022).

The developers of architectural lighting software, such as DIALux and Relux, are increasingly developing the ability to visualise and import textures, spatial models and objects made in other design programs. DIALux can also, through its data management system (DMS), import industry foundation classes (IFC) files, which are open format files used by building information modelling (BIM) programs. Industry foundation classes files can contain information about a building or facility model, including the spatial elements, materials and shapes, but they also contain data about lighting fixtures, e.g. luminaire model, photometrics, mounting type, weight, etc.

Figure 3 shows a visualisation of the interior lighting of an apartment made with DIALux evo software. The visible light fixtures are all models based on photometric data. The ability to use real luminaires with EULUMDAT-type data in the simulation, in which the light distribution information is stored, provides the possibility of a much more accurate analysis of the light distribution in space. Such a capability is usually not available in the typical interior modelling programs used by architects.



Fig. 3. Interior lighting visualisation of the flat made with DIALux software

Source: own work.

Three-dimensional visualisation software plays a significant role in architecture and interior design by accelerating and improving the work process in this sector. Three-dimensional visualisation technologies enable the development of cooperative and digital engineering, the quick production of design elements, the reduction of errors throughout the design process, and the presentation and handling of projects. The client has the opportunity to see the near-final digital result of the project, before starting work on it. In the case of architecture and interior design, 3D visualisation gives clients the opportunity to see the building layout, interior and exterior designs, lighting, textures, etc., before completing the development process.

To the visualisation methods already described we can add the latest visualisation techniques related to virtual reality (VR) and augmented reality (AR) technologies. Taking advantage of its capabilities

requires an additional item, such as VR goggles. After placing the VR goggles on our head, our entire field of vision is filled with an image from the virtual world and we can observe any part of it by simply turning our head. This technology also allows movement and the exploration of space, with the only limitation being the size of the world modelled by the designer. Movement in the virtual reality is controlled with the hands, using special controllers, while more advanced equipment allows mapping of the movements of the entire human body.

Augmented reality is a technology that involves overlaying virtual 3D objects, generated in real time, onto images in the real world, using image-processing, and so allowing architects to simplify the design process. It is an advanced form of design visualisation, which allows one to understand the results of a project and its impact on the environment before incurring the costs of implementation. Augmented reality also makes it easier to locate errors and, as a result, contribute to saving time and reducing the investment costs.

CHARACTERISTICS OF SELECTED TOOLS FOR THREE-DIMENSIONAL SIMULATIONS WITH VISUALISATION

Computer software manufacturers have created a wide range of applications intended for architects, some of which are well established in the market. The designer, regardless of whether they are working on a product, interior design, building or landscape architecture, expects visualisation capabilities from their software. Among the most commonly used CAD programs today are:

- SolidWorks, mainly used in the product development process by mechanical, electronic and electrical engineers. This software is able to support designers in the construction of tools and equipment, including injection moulds, stamping dies, workstation equipment, auxiliary equipment, etc. It also allows assembly models and technical drawings to be made, while due to the possibility of adding additional software, known as plug-ins, the operation of the program can be extended with specialised simulation tools, such as the simulation of optical systems and the simulation of lighting effects for motion and loads. The program is also used by architects for specialised design tasks.
- SketchUp, which is a relatively easy-to-use 3D modelling and design program. It provides a set of tools that allow quick spatial modelling and texturing, while the extensive editing functions allow you to change the already existing materials. You can create your own objects or work on objects imported from the 3D warehouse. It also has many free tools to support the process of building 3D-models and also includes defined light models that can be used to illuminate the arranged space, while to increase the realism of the presentation it is possible to use external engines for rendering images (Pasek, 2011).
- Lumion is a program created for the visualisation and animation of architectural objects. It allows the quick and easy generation of high-quality renderings. The developers of the program offer a five-step visualisation process: import the project, add materials, create the environment, add objects, apply effects and render them.
- Rhino (Rhinoceros) is a program that includes specific features and tools for free 3D modelling. The latest version of the program (Rhino 7) allows the use of physically based rendering (PBR) type materials, which, according to the manufacturer, enable high-quality realistic renderings. This type of graphic material is becoming a standard for material libraries, creating content for scanning that is supported in many modern applications. Rhino allows the creation, editing, analysis, documentation, rendering and animation of three-dimensional objects. It is very often used in product visualisation, while external software, such as Photopia, can be attached, which is able to perform very accurate lighting simulations including the simulation of light colour mixing with visualisation.

The program has a unique Grasshopper plug-in, responsible for algorithmic (parametric) modelling. This allows you to design and edit complex shapes using specific parameters, and in the expanded version with Photopia software and the Grasshopper function it is able to create unique models of lighting fixtures and carry out detailed visualisation and analysis of the light distribution on such a designed product.

- AutoCAD comes in many versions designed for various design tasks. One of them is the version with the Architecture toolkit, which includes several thousand architectural components, functions for the automatic generation of objects, elements such as walls, doors and windows with stored information on their actual behaviour and construction, as well as a number of other solutions to support the work of the architect.
- DIALux software is used to design complex architectural lighting, industrial facility and outdoor area lighting, including for roads and streets. The program is able to calculate daylight in clear or overcast skies and take into account daylight systems. DIALux has its own library of materials and objects, which can be expanded with materials created externally in CAD software. DIALux also allows the detailed presentation of lighting results in the form of luminance or illuminance distributions. Figure 4 is an example of the visualisation of the luminance distribution in the room presented in Figure 3. The luminance distribution is shown using false colours. Using this form of visualisation, the designer can verify that the resulting lighting effects are not characterised by too much difference in luminance contrast in workplaces, for example, which may cause excessive glare (Immecke, 2021).



Fig. 4. Visualisation of luminance distribution in an apartment depicted with false colours, made with DIALux evo software

Source: own work.

SOFTWARE SIMULATION LIMITATIONS AND THEIR IMPACT ON VISUALISATIONS

Lighting can form a critical component of any architectural project. In some cases, there is a need to obtain very precise information about the visualisation of the light distribution on the illuminated surfaces. As mentioned earlier, designers are often unaware of the simulation limitations of the tools they use in visualisations. They mistakenly assume that the generated image will be close to the actual lighting effects. Most of the programs

commonly used by architects are unable to correctly simulate colour mixing in a lighting fixture, spectral effects, or lighting of structures from a short distance. The correctness of such visualisations can only be provided by specialised software based on light distribution calculations using the Monte Carlo methods or inverse ray analysis. An example of a program in which it is possible to perform highly complex analyses of light distribution, in complex optical systems, using real models of light sources, is Photopia software. The manufacturers of this software, after analysing the market, decided to prepare a plug-in for Photopia's version software for SolidWorks and Rhino. This allows the different software to increase their analysis and computer simulation capabilities, and designers to remain in their familiar working environment (Krupiński, 2011).

Figure 5 shows the imaging of spectral effects in architectural lighting. The example shows the lighting effect of a luminaire with randomly modelled holes in the reflector. The luminaire is equipped with blue, red and green LEDs. The diodes are arranged in the luminaire in various locations, resulting in shifted coloured light patterns emitted through the holes. The light from the interior of the lamp can leave the shade directly or mix with other colours due to multiple reflections inside the fixture. Such effects cannot be simulated properly with standard software. A Voronoi pattern, generated using the Grasshopper function available in Rhino software, was used to create the holes (Glinko & Jongewaard, 2022).



Fig. 5. Visualisation of light distribution considering the spectral distribution of light sources in a room illuminated with a luminaire with blue, red and green LEDs

Source: LTI Optics, LLC, Photopia™ for SolidWorks & Rhino Architectural Lighting, LTI Optics, LLC. 2022.

Most computer software is not able to properly visualise the illumination of structural surfaces from a short distance. Even DIALux software, which relies on EULUMDAT-type photometric data, cannot function in this case. This is related to the way that photometric solid models are built, in which the luminaire has a measured light distribution with a limiting photometric distance (LPD). Illuminating objects from a short distance requires the use of tools that can perform the analysis below the LPD. From this point of view, a properly made model of the light source is also important. Usually such models are very simplified, and their shape is similar to basic spatial solids, such as cuboids or cylinders. Most often, the light in these models is emitted uniformly from their entire surface, which in some situations is far from reality. Figure 6 shows a correct visualisation of structural wall lighting made using Photopia software in the Rhino environment.



Fig. 6. An example of the proper visualisation of the light distribution on a structural wall. The visualisation was made using Photopia software in the Rhino environment

Source: LTI Optics, LLC, Photopia™ for SolidWorks & Rhino Architectural Lighting, LTI Optics, LLC. 2022.

Visualisation errors can also be influenced by the actual design of the models of reflective surfaces, such as walls, ceiling and floor. Architectural lighting programs often treat them as perfectly diffuse reflective materials. The effects of reflections and directional reflections seen in renderings are approximate and are the result of single-pass ray tracing at the end of the image generation process.

The accuracy of the visualisation is particularly important for object illumination. A properly performed visualisation allows us to verify design variants, to check the correctness of the design process at various stages, and to reduce the potential costs associated with the resulting errors and the need to correct them during the project implementation process.

To sum up, it should be added that artificial intelligence (AI) is an increasingly common tool used in visualisations, including in architecture. There are increasing numbers of tools and programs using AI modules appearing on the market. Creating photorealistic images of interiors using AI is simple and not time-consuming, it creates enormous opportunities, but at the same time it brings additional threats, related not only to incorrect light reproduction. In the long run, AI tools may change the picture of the labour market, the structure of employment process, the pricing and the availability of services. One example of the use of AI in visualisation is shown in Figure 7, based on the visualisation made by DIALux evo software in the computer simulation process shown in Figure 3.



Fig. 7. An example image generated with the help OpenArt, using the high creativity of the proposed solutions

Source: own work.

The visualisation was made using the OpenArt tool, which allows multi-variant creation of images based on previously provided photos or renderings. Entering additional text (prompting) is possible, but not obligatory. The user can control the colours of the generated images and their degree of similarity to the original.

CONCLUSIONS

The market for 3D visualisation technology continues to grow significantly every year, covering ever more areas of our lives. The advertising industry (digital advertising) and 3D animation are increasingly using visualisation, the technology and popularity of printing objects on 3D printers is also growing, and it seems that in the coming years the processes related to visualisation capabilities will accelerate even more strongly. Increasingly, software manufacturers are introducing visualisation software into their ranges, one example being Adobe, which recently introduced the Substance 3D Collection suite of tools for creating, recording and editing 3D materials and textures, to help building and rendering 3D scenes. The ever-expanding capabilities of engineering computer software and the ability to transfer data to various computer applications are greatly accelerating the design processes. In this aspect, it is worth noting the increasingly popular building information modelling (BIM) system, which is already the foundation of digital transformation in the architectural, engineering and construction industries. Every piece of software has its limitations and may use simplifications, and these limitations can also be related to the accuracy of the visualisation. Executing the project according to the expected final result requires knowing and understanding these limitations and, in special cases, using additional specialised software.

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WIZUALIZACJA W ARCHITEKTURZE – MOŻLIWOŚCI I ZAGROŻENIA

STRESZCZENIE

Rozwój technologii komputerowej, mocy obliczeniowej kart graficznych i procesorów pozwalają, przy wykorzystaniu odpowiedniego oprogramowania, na kreację niezwykle realistycznych trójwymiarowych obrazów. Efekty wygenerowanych wizualizacji mogą być trudne do odróżnienia od rzeczywistych zdjęć obiektów. Niejednokrotnie architekci weryfikują spełnienie celów projektowych, wykorzystując do tego wyrenderowany obraz cyfrowy. Niestety często projektanci nie są w pełni świadomi ograniczeń i uproszczeń, jakie niesie ze sobą stosowanie narzędzi do tworzenia wizualizacji. Bezkrytyczne podejście do prezentowanych wyników może prowadzić do błędów projektowych. Niniejszy artykuł przedstawia możliwości realizacji wizualizacji w wybranych programach komputerowych wykorzystywanych przez architektów oraz przypadki, w których poprawna wizualizacja jest możliwa jedynie przy zastosowaniu oprogramowania specjalistycznego. W artykule zwrócono szczególną uwagę na możliwości powstawania błędów w wizualizacji oświetlenia architektonicznego.

Słowa kluczowe: architektura, trójwymiarowa wizualizacja, Photopia, oświetlenie architektoniczne, wizualizacja w architekturze

OPPORTUNITIES OF BUILDING TALL AND GREEN – AN OVERVIEW FROM A EUROPEAN PERSPECTIVE

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ABSTRACT

The purpose of the article is to answer the question of whether a tall building, throughout its entire life cycle, can be sustainable. A literature review and online searches were conducted in order to gather data on the impact of environmental trends on chosen aspects of tall European building design. The conducted analyses confirm the hypothesis that the European approach considers sustainable aspects and can be the basis for general guidelines for the construction of green tall buildings, ensuring that the tall building's location, floor areas and heights are functionally justified. Despite the demanding climate conditions, high-rise buildings are designed using bioclimatic solutions and take the use of passive phenomena and a reduction in the operating time of mechanical systems into account. The necessary technical infrastructure uses highly efficient, energy-saving equipment and solutions. Obtaining energy from renewable sources is present in architectural solutions but not very popular – these technologies are still growing and gaining importance.

Keywords: high-rise building, skyscraper, green city, ecology, sustainability

INTRODUCTION

The growing awareness of the impact of human activities on the environment and – conversely – the effects natural factors have on humans result in changes in the philosophy of design. Activities defined as green, environmentally conscious, sustainable, eco-tech, etc., are aimed at limiting the pressure exerted on the natural environment and providing people with friendly living conditions. This issue is described in more detail in Pietrzak (2013a) and Pietrzak (2013b). Therefore, urban development should focus primarily on sustainable development and respect for the natural environment with humans a part of it (Jaworska-Michałowska, 2010), as well as developing systems functioning similarly to the ecosystem.

Yeang (2008) writes that tall buildings are the most non-ecological type of structures and one can only strive to minimise their negative impact on the environment. However, doubts about the appropriateness of high-rise developments will not result in the sudden abandonment of this type of building. Further skyscrapers will be built to meet the needs of urban development and the ambitions of developers. The need for skyscraper design cannot be denied, and instead, designers have to mitigate their negative environmental impacts (Yeang & Powell, 2007).

Because of the scale of the buildings and the design approach, including interdisciplinary collaboration and awareness of the ecological problems (Rees et al., 2013), the search for the guidelines for the sustainable

design of future tall buildings has been limited to an analysis of European trends, as well as buildings and projects emerging in Europe.

The hypothesis is that the European approach can be the basis for general guidelines for the construction of green tall buildings. The purpose of the analyses discussed in this paper was also to answer the question of whether a tall building, throughout its entire life cycle, can be seen as sustainable. A literature review and online searches were conducted in order to gather data on currently constructed and planned tall buildings. The collected data was then consolidated and analysed in order to determine the impact of environmental trends on the design, construction, and functioning of buildings. The following aspects were analysed: the evolution in the design of tall buildings, the problem of urban sprawl, aspects of determining the form of tall buildings and possibilities of energy consumption reduction. The article presents selected, particularly pertinent aspects of the researched issues.

THE EVOLUTION IN THE DESIGN OF EUROPEAN TALL BUILDINGS

In the first period of intensive development of European high-rise buildings between 1960–1975, modernist skyscrapers with glazed, often dark façades (Fig. 1a) were being constructed. The buildings were characterised by large heat losses, overheating and lack of natural light, and were only able to function with the use of air conditioning and artificial lighting. As a result of the energy crises occurring in the 1970s, designers' attentions turned to energy-efficient design: limiting heat losses and gains, lighting the interiors with natural light, implementing the latest technological solutions, and introducing IT systems for building management (Scicolone, 2012). Compact tall buildings with translucent façades were being designed (Fig. 1b), and as a result of the introduction of double-glazing, they had better insulation (Oldfield, Tarbucco & Wood, 2008). However, the usability of buildings still depended on the efficiency of mechanical systems, of which the most important became ventilation and cooling (Pawłowski & Cała, 2013). Karfik wrote: "A modern office building should be equipped with an excellent year-round air-conditioning system, completely automated and remotely controlled from a central control point" (Karfik, 1976, p. 82). The author also recommended the use of non-opening windows and the possibility of ignoring the orientation towards the surroundings (Karfik, 1976).

In the 1980s (Fig. 1c, 1d), a new type of building was introduced, the so-called intelligent building that combined the requirements of ensuring the comfort and safety of users with the maximum reduction in the cost of obtaining it (Niezabitowska, 2005). Buildings traditional in form, but equipped with extensive, advanced technical infrastructure were being designed. For example, there was automatic regulation of interior microclimate parameters. The elements of the spatial layout conditioned by the technical solutions adopted were few, such as the height of the storeys, and the size and distribution of toilets, technical rooms and storage rooms (Pietrzak, 2013a).

Towards the end of the 1990s, even more attention was being paid to environmental efforts, particularly to energy-saving measures. In addition to new developments, the redevelopment of existing buildings that were decades old was increasingly being designed, adapting them to contemporary aesthetic and functional requirements. Since the construction of the new Commerzbank Tower in Frankfurt am Main (Fig. 2), the implementation of environmental considerations has contributed to redefining the image of the high-rise building. The implementation of pro-environmental norms has contributed to the redefinition of the image of a tall building (Hart, 2011). Economical energy management, minimisation of environmental pollution during the construction and use of the building, as well as the use of natural resources, were postulated (Pawłowski & Cała, 2013). The year-round use of an air-conditioning system was considered to be environmentally unfriendly. The need to provide adequate insulation of the enclosure, natural light to the interiors, protection from overheating, and natural ventilation was pointed out (Wells, 2005).

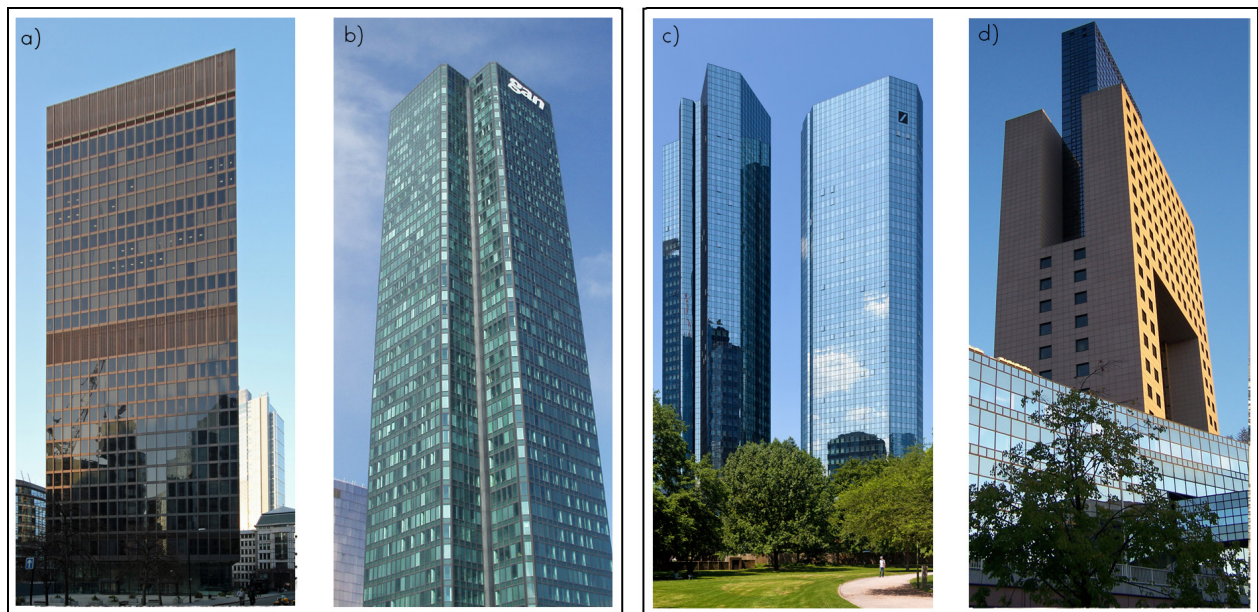


Fig. 1. Tall buildings erected in the 1960s, 1970s and 1980s: a – Commercial Union (now Aviva Tower), London, 1969; b – Tour Gan, Courbevoie, 1974; c – Deutsche Bank Towers, Frankfurt am Main, 1984; d – Messeturk, Frankfurt am Main, 1985

Source: ^aSkyscrapercity.com [n.d.]; ^bOlivier Passalacqua 2006; ^cThomas Wolf 2013; ^dSebastian Kasten 2005.

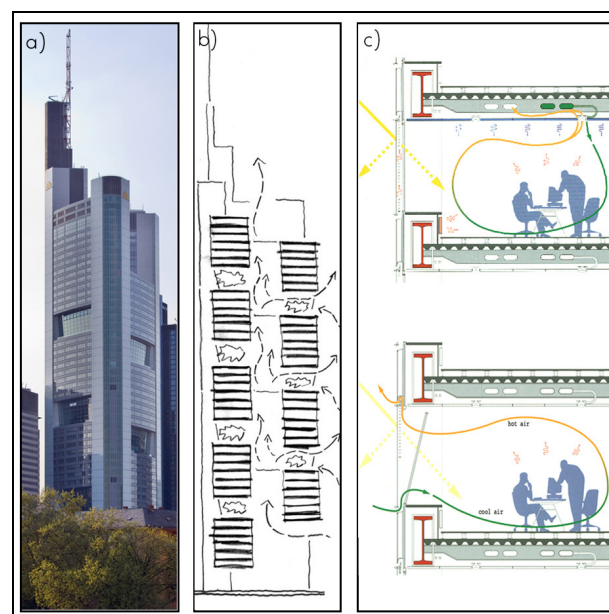


Fig. 2. Commerzbank Tower, Frankfurt am Main, 1997: a – view; b – diagram of the natural ventilation in the atria; c – diagram of the HVAC system and natural ventilation

Source: ^aMylius 2009; ^b© Foster + Partners 2024; ^cDavis (1997, pp. 200–201).

The unique character of European tall buildings was emphasised, the specificity of which was not due to participation in the global height race, but to the integration of the tall building with the historic fabric and environmentally friendly standards. The model building was characterised by shallow tracts, or additions to deeper ones with atria, and large glazed areas, providing access to natural light and fresh air, providing all rooms with access to light and air. Due to the need to adapt the building to the local microclimate, external shaft locations began to be considered (Trabucco, 2010).

Responding to local conditions, the building form was intended as a tool to control the interior microclimate. Rather than relying solely on mechanical systems, natural or mixed ventilation was introduced. A significant change was the use of a double façade, which acts as a thermal and acoustic buffer, and allows for natural ventilation and the opening of windows. Other solutions and technologies being introduced to save energy are heat recovery systems, provision of night cooling, low-energy ventilation and water systems, advanced zoned air-conditioning and intelligent building management systems (Zukovsky & Thorne, 2000). More frequent attention was given to the sources of energy used in the building, as well as the need to introduce vegetation in the interiors of high-rise buildings.

The benefits associated with environmental activities have become increasingly quantifiable for developers ever since the spread of certification systems for green buildings (Heller, 2014; Sharma & Nair, 2021), such as: LEED, BREEAM, DGBN, SPeAR, E/STEP, and HQE as indicators of the prestige of a given development. Certification requirements, however, can become the basis for a kind of standardisation, and designers should primarily consider adapting the tall building to the microclimate, rather than stop at introducing high-performance systems (Goodwin, 2015).

TALL BUILDINGS VERSUS URBAN SPRAWL

Progressing urbanisation is the result of the search for a new way of life in cities to which more and more inhabitants are arriving (Dupre, 2008). Also, the social expectations in Europe are changing – people want to live and work in city centres. In many cities, such migrations are associated with, among others, the uncontrolled sprawl of the urban fabric. There are only two scenarios in the planning of expanding cities – the amount of urbanised terrain will increase, or the height of the urban fabric will increase. Meanwhile, one of the key building planning criteria is the reduction of carbon footprint (Dalton & John, 2008). In order to meet these criteria, it is necessary to limit individual journeys and organise effective urban transport systems, which is possible thanks to high urban fabric intensification.

Striving for sustainable development, reducing urban sprawl and saving energy used to transport people and goods is leading to the planning of cities with higher building intensities (Partridge, 2015), achieved, among other things, by concentrating tall buildings. The introduction of high urban fabric intensification in relatively small areas, as well as combining various building functions (office, residential, hotel, service, or cultural functions) allows, among others, for the preservation green areas, more efficient use of land (Wood, Henry & Safarik, 2014), limiting the transport of people and goods (Partridge, 2015), as well as providing people with the opportunity to live, work, use services, and rest in the same area. There is already a type of vertical neighbourhood (Johnson, 2014), which is formed by a single multifunctional building or a group of buildings with different functions connected by footbridges.

However, in European cities today, high-rise buildings are generally not a type of urban fabric (Asendorf & Kaltenbrunner, 2005), and this type of building is needed only in metropolises with several million inhabitants. Tall residential buildings are a solution to problems such as a growing population and the urban sprawl of cities that lack land for new property development. Cities such as the greenbelt-limited London cannot ‘sprawl’, so the height of buildings, especially residential buildings, must increase (Murray, 2013). Within Moscow’s administrative boundaries, there was a lot of vacant land suitable for development, but very high housing needs also necessitated the introduction of tall buildings (Shuvalova, 2015).

DETERMINING THE FORM OF TALL BUILDINGS

Nowadays, not only is the originality of a skyscraper sought, but also its logical explanation. The different types of high-rise development in different cities is due to, among other things, the physical and environmental context (Wood, 2013). Most architects agree that an analysis of local conditions should be the basis for design development (Jaworska-Michałowska, 2010). Increasingly, references to the material and environmental context, including the landscape, weather, the topography of the terrain, and the geological conditions of the plot, are considered to be key elements of the design process (Dupre, 2008). Environmental conditions, due to their endemicity, objectivity and relative immutability, are logical determinants of the direction of the design process (Ryńska, 2001).

Bioclimatic design

Daniels (1998) distinguished three design strategies depending on the technical level at which energy savings are achieved. The low-tech approach is to save energy passively by designing simple buildings made from natural resources and based on naturally occurring processes. The light-tech approach means an efficient use of natural resources, relying primarily on recycling. The high-tech design method implies the use of technologically advanced solutions and equipment to create an optimum indoor microclimate. The aforementioned strategies are further supplemented by Yeang (2008) with a mixed mode (a combination of low-tech and high-tech elements on a permanent or periodic basis, e.g. depending on the season) and a production mode, with which energy is generated in the building (however, this requires the introduction of further advanced high-tech elements and distances the building from nature).

Yeang emphasises that it is a misunderstanding to stop at the introduction of eco-gadgets and technical elements that complement the building, which is an approach that has become very common in the design of high-rise buildings. One should always aim for at least a mixed mode, using passive solutions in all possible aspects of the project. In general, a tall building is designed using the most advanced (high-tech) materials, technologies and technical solutions, but these should only be in addition to the logically designed spatial form of the building – the low-tech approach can be applied to this aspect of the design. This is not to use the simplest level of technology for high-rise buildings, but to take advantage of the characteristics of the location and naturally occurring processes. Yeang described this approach to design in the 1990s. He wrote in his book: “Bioclimatic design is a passive, low-energy design approach that uses energy from the surrounding microclimate to create a comfortable environment for building occupants” (Yeang, 1999, p. 11). The approach described aims to reduce non-renewable energy consumption and restrict the use of mechanical systems.

In cities, the most strongly influencing element of the built environment is microclimate – climatic factors considered at the scale of a building’s neighbourhood of approximately 1,000 m. In particular, solar radiation, temperature, air circulation and water balance are taken into account (Zielonko-Jung, 2013). It should be emphasised that in the European climate, it is virtually impossible to operate a tall building based solely on interactions with the local microclimate. Designing for a temperate European climate requires consideration of a large spectrum of changes in atmospheric conditions. In winter, it is desirable to provide high thermal insulation of the building envelope and passive heating of the interior, and in summer, intensive ventilation of the rooms and protection against overheating. In addition, shading elements should protect against solar radiation in summer and allow it to enter the building in winter (Wood & Salib, 2013). In a European bioclimatic building, a high-performance standard is determined by a harmonious cooperation between the use of local climatic phenomena and mechanical systems (Ryńska, 2001).

Shaping of the spatial form

One of the fundamental issues in the design of bioclimatic buildings is to strive for compact forms (Fig. 3) and achieve the highest possible ratio of the projected area to the length of its perimeter, thus minimising the façade area as well as heat loss and gain.

Important factors taken into account in the design of a bioclimatic high-rise building are its orientation with respect to compass points (Rokicki & Pietrzak, 2013), the exposition-dependent shape of the building and the location of different functions within the tall building. Such an approach, associated, for example, with the placement of all technical rooms, toilets, etc., on the north side, allows for maximum daylight in the interiors (Fig. 4). The buildings are designed to maximise the use of natural daylight (shallow tracts, orientation of the façade in relation to compass points) – see Figure 5b. On the other hand, locating the core on the south side may be related to its use as a shield against overheating and glare from sunlight for workers (Trabucco, 2008; Fig. 6). The design of the building should also take into account changes in the components of the microclimate (e.g. wind, temperature) at the height of the building and should not consist of a series of repetitive floors (Wood, 2015).

In the 21st century, technological evolution has also extended to the design of tall buildings. The introduction of CAD model building software, parametric design, computers with ever-increasing computational capabilities, and the use of optimisation algorithms allow the design of increasingly complex forms which are increasingly responsive to external factors and internal conditions, and buildings that fit more and more precisely into their surroundings. CAD model building software has enabled greater design freedom for architects and engineers alike, resulting in forms previously unheard of – fluidly changing or twisting (Vollers, 2009).

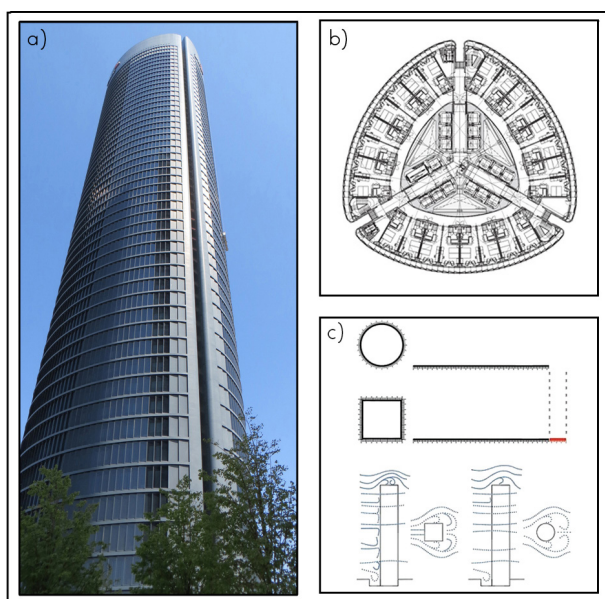


Fig. 3. Torre PwC, Madrid, 2008: a – view; b – floor plan; c – benefits of the circular form

Source: ^aJoanna Pietrzak 2011; ^{b,c} Rubio & Álvarez-Sala, ^cWorkdifferent.wordpress.com 2010.

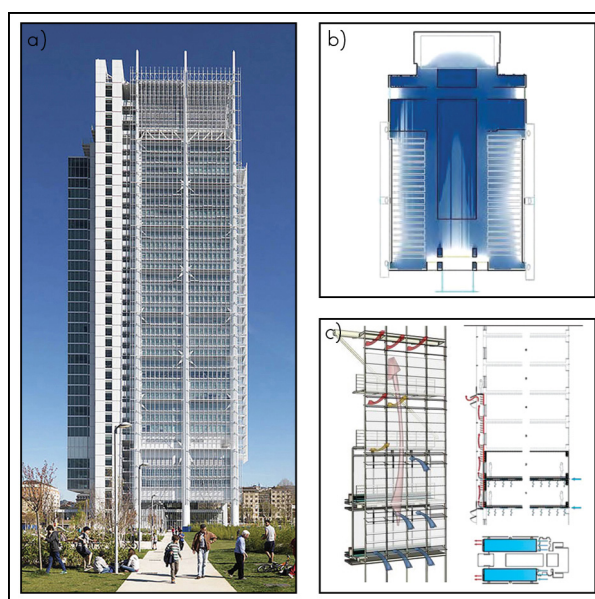


Fig. 4. Grattacielo Intesa Sanpaolo, Turin, 2015: a – view; b – floor plan and analysis of the natural lighting; c – diagram of the functioning of the gravity ventilation in the double façade

Source: ^a© Enrico Cano; ^{b,c}© Renzo Piano Building Workshop.

Aerodynamic form

It is a common procedure to determine the characteristics of wind phenomena occurring around a high-rise building through wind tunnel testing (Johnson, 2014). In particular, the proximity of a dense and complex urban fabric necessitates reasonably precise analyses to determine the impact of the surroundings on a new building. These studies have resulted in the increasing emergence of high-rise buildings with streamlined, bionic shapes, which are characterised by less resistance to wind and a corresponding reduction in the loads acting on the building and its enclosure. The most common type of aerodynamic skyscraper is a building with a cylindrical, egg or cucumber (Figs 3, 6, 7) form (Binder, 2006).

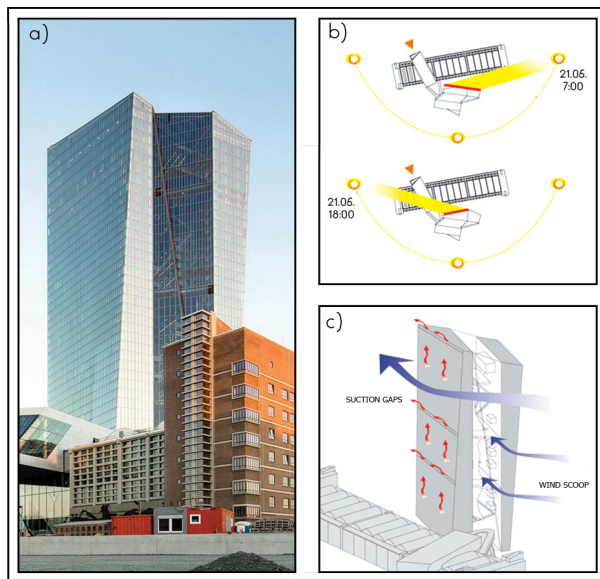


Fig. 5. ECB Tower, Frankfurt am Main 2014: a – view; b – the building plan dependent on solar exposure; c – diagram of cross and gravity ventilation

Source: ^a© European Central Bank/Robert Metsch; ^{b,c}© Coop Himmelb(l)au.

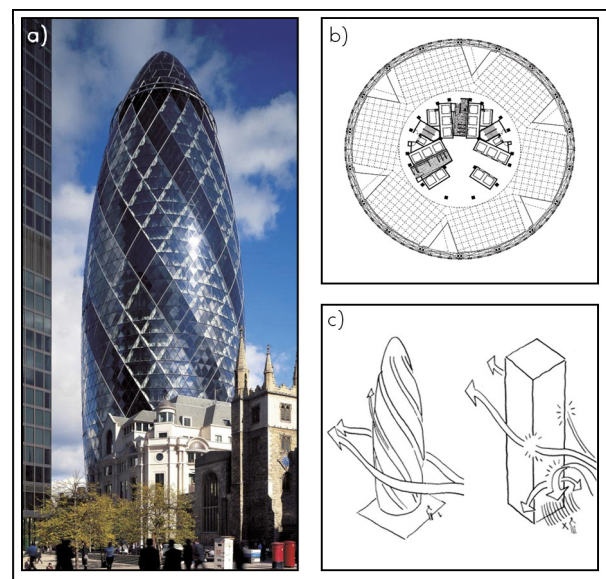


Fig. 6. Building at 30 St Mary Axe, London, 2004: a – view; b – floor plan; c – diagram of the airflow around the building

Source: ^aWikiarquitectura, 2017; ^{b,c}© Foster + Partner.

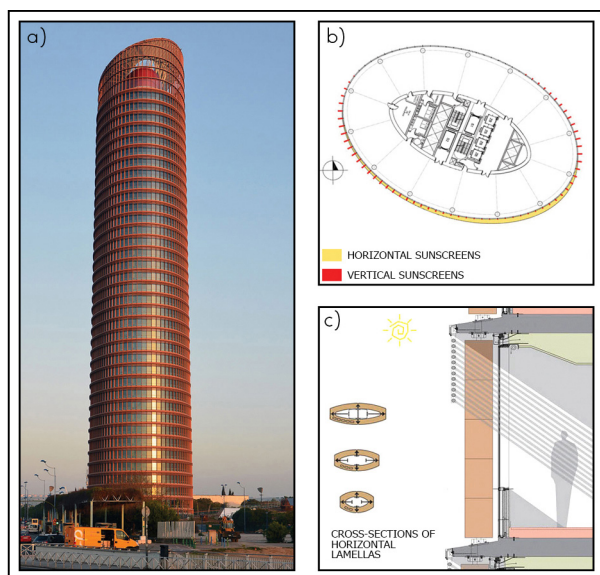


Fig. 7. Torre Sevilla, Sevilla, 2016: a – view; b – façade design scheme dependent on the orientation; c – detail of the façade solution

Source: ^aGzzz (2015); ^{b,c}© Pelli Clarke Pelli Architects.

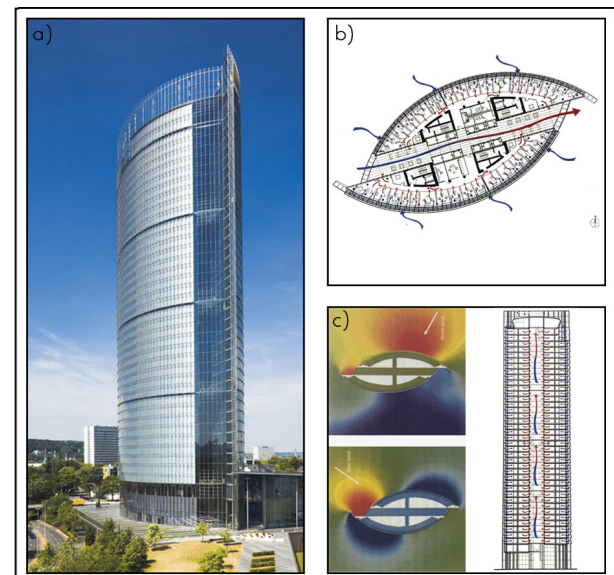


Fig. 8. Post Turm, Bonn, 2002: a – view; b – floor plan and cross ventilation diagram; c – pressure distribution around the building and gravity ventilation diagram

Source: ^a© Murphy/Jahn; ^{b,c}Wood and Salib (2013).

Natural ventilation

Aerodynamic studies and analyses allow the use of wind phenomena to generate a pressure differential that is used to initiate the process of natural cross ventilation (Etheridge & Ford, 2008). At the windward end of the enclosure, air is drawn into the building and at the leeward end, air is drawn out. Appropriately shaped forms of bioclimatic buildings allow the desired pressure distribution around the skyscraper to be generated, taking into account different wind directions (Figs 5, 8). The process of natural ventilation can also occur due to buoyancy forces caused by differences in air density at different temperatures (Wood & Salib, 2013). This phenomenon is also known as the chimney effect and is mainly dependent on height. In order to introduce this type of natural ventilation, an internal atrium, chimney or other vertical shaft should be provided (Figs 2, 4, 5, 8).

Interior divisions

Interior divisions are also important. In hotels and residential towers, a large number of small rooms are required. In order to provide natural daylight, rooms should be located along the façade to provide natural light and ventilation. For this reason, elongated floor plans (e.g. rectangular) with a higher perimeter-to-area ratio are advantageous for multifunctional high-rise buildings. In office buildings, open spaces should be located at the perimeter of the building, and closed rooms should be in the centre.

The limited depth of the tracts and the correspondingly high height of the rooms allow for efficient use of daylight and natural ventilation. A large group of high-rise buildings are characterised by a net storey height of 2.7–2.8 m, and this value generally does not exceed 3.0 m. Flats and hotels (Fig. 9b) can only be effectively designed on shallower tracts, with tracts typically no smaller than 7.0–9.0 m for functionality. Such dimensions allow practically the entire usable area to be lit by natural light. The design of buildings with an office function (Fig. 9a) is more varied. Minimum tracts in such high-rise buildings are about 7.0 m deep, typically around 12.0–13.0 m. Only with double-sided daylighting do the tracts reach depths of up to 40 m, and the record building width of the Salesforce Tower (50.0 m) is the result of the introduction of an atrium (Fig. 10).

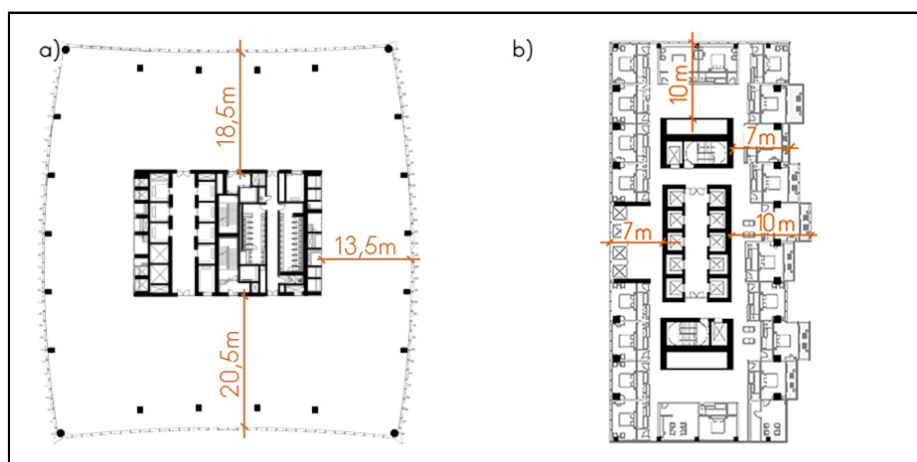


Fig. 9. Tract depths in a building: a – with an office function: 20 Fenchurch Street building, London, 2014; b – multifunctional: DC Tower, Vienna, 2013

Source: own elaboration based on: ^atwentyfen.co.uk (2022); ^b© DEKA Immobilien.

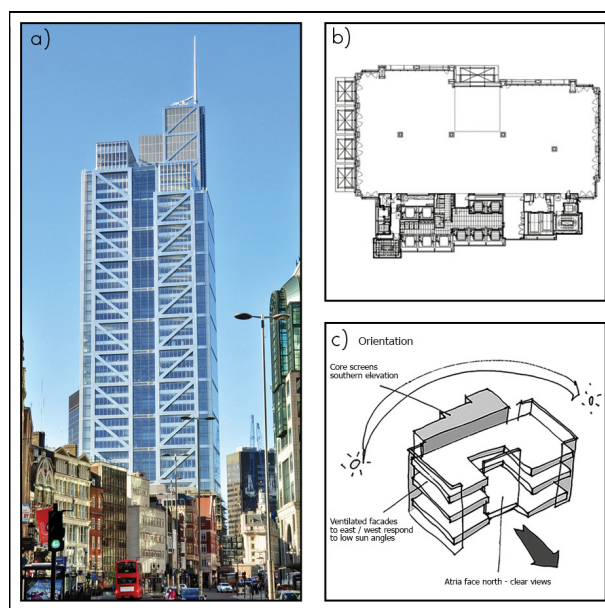


Fig. 10. Salesforce Tower, London 2011: a – view of the north elevation; b – floor plan; c – scheme of the orientation of the building

Source: ^aEluveitie (2012); ^bCbre.co.uk [n.d.]; ^c© KPF.

Solutions such as atria (Fig. 11a) or winter gardens (Fig. 11b) are highly beneficial: they provide natural ventilation chimneys, improve access to natural light, act as solar collectors and thermal buffers, and are spaces where greenery can be introduced (Wood & Salib, 2013). Despite their many benefits, atria are generally not introduced in contemporary European high-rise buildings because the loss of floor space is too great.

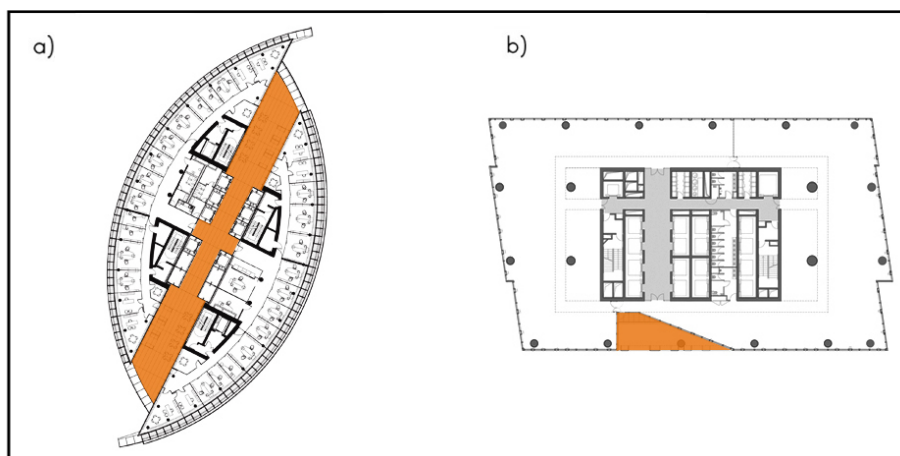


Fig. 11. A tall building with: a – atrium – Post Turm, Bonn, 2002; b – winter garden – Tour Majunga, Puteaux, 2014

Source: own elaboration based on: ^aWood and Salib (2013); ^b© Jean Paul Viguier et Associes.

Façades

Instead of atria, double façades (Figs 2, 4, 5, 8) are very often introduced in the design of European high-rise buildings, which perform similar functions and take up significantly less space. With such a solution, consisting of two glass shells separated by a void, it is also possible to open windows shielded from the effects of undesirable atmospheric agents and, above all, strong winds (Etheridge & Ford, 2008). Double-glazed façades provide space for air circulation. In winter, they can be used as a thermal buffer and a passive heat collector. In addition, they are usually equipped with mobile elements, allowing them to be opened and provide intensive ventilation and cooling in summer. Often, the façades are equipped with additional shelves, louvres, etc., which protect against solar radiation in summer and allow the sun's rays into the building in winter (Lotfabadi, 2015).

Also, other types of façades are increasingly often appearing as an integral complement to the building's form, and their shaping is associated with the design of both the interior and exterior of the building. A properly designed enclosure has to be adjusted to the climatic zone, site characteristics, orientation of the building form and the window-to-wall ratio (Oh, 2020).

A varied façade adapts the building to exposure from all sides (Fig. 7), through elements that prevent dazzling sunlight, limit or maximise solar gains, constitute a visual barrier, or control gusts of wind and allow for the windows to be opened (Johnson, 2014). Some studies even indicate that the thermal transmittance and insulating properties of the enclosure should change with increasing height, as the amount of heat gains and losses changes (Saroglou, Meir, Theodosiou & Givoni, 2017).

The use of the increasing computational capabilities of computers, design processes and optimisation algorithms has allowed buildings enclosures to more precisely fit into their surroundings. The microclimate parameters changing at the height and perimeter of a skyscraper (Gui et al., 2021; Saroglou, Meir & Theodosiou, 2022) are more accurately analysed, and their spatial forms can be designed as increasingly complex and better adapted to local conditions. The individual façade elements can be adapted to the place of installation.

It is now common to see a trend towards fully glazed façades. However, this is not a favourable solution in terms of energy savings (glass is not the most efficient insulating material) and also in terms of the bioclimatic design of the façade, which requires, for example, the addition of elements to protect against excess solar radiation (Aminmansour, 2019). In a building designed with respect for energy consumption, glazing should constitute no more than 50% of the façade area (Al-Kodmany, 2022).

There is also a visible trend for transforming the façades, especially of residential buildings, into vertical gardens or even urban forests. Green walls, as well as plantings of shrubs and trees on balconies and terraces, are being introduced (Al-Kodmany, 2023a; Basso, Bisiani, Martorana & Venudo, 2023). Vegetation acts as a wind buffer. In summer, vertical landscape elements give shade, as well as absorb and reflect a high percentage of the sun's radiation, thus lowering the ambient temperature. In winter, they let solar radiation through. The soil layers contribute to further cooling of the air around the building, in addition to increasing retention. However, "vertical planting is far more expensive than horizontal planting" (Al-Kodmany, 2023a, p. 48). The integration of greenery into a tall building requires a sophisticated technical design of the skyscraper structure (additional loads) and the technical infrastructure (watering, drainage of excess water). Specialised, continuous maintenance is also required for plants that do not grow in their natural habitat. Water consumption and the cost of supplying water can be significant. Ultimately, maintaining plants can be expensive both financially and environmentally, even though plants absorb carbon dioxide, filter air pollutants, reduce temperatures and increase humidity. In addition, outdoor greenery cannot be planted at considerable heights either, because of, for example, the damaging effect of strong winds. Therefore, at considerable heights, greenery is rather introduced in atria or sky gardens closed in a huge greenhouse.

REDUCTION OF ENERGY CONSUMPTION

Yeang states that the design of the built environment should be directed towards ecomimicry, i.e. mimicking the interrelationships occurring in the ecosystem (Yeang & Powell, 2007). The most important features to be considered should be: no waste (everything is recyclable), combining inorganic and organic elements (i.e. introducing biomass), and using only solar energy (i.e. renewable sources). Minimising the negative impact of a tall building on the environment is an increasingly important issue, especially the reduction of pollutant emissions and waste production, as well as the reduction of energy consumption throughout the life cycle of the building (Trabucco & Belmonte, 2021). The need to reduce the carbon footprint is now particularly emphasised (Amiri & Sakeena, 2021; Miranda & Safarik, 2021).

Efficiency of adopted solutions

For developers, the cost-effectiveness and efficiency of solutions adopted in the project are often more important than their environmental friendliness. Meanwhile, rational design can combine these three aspects. The energy consumption needed for the production of materials, construction, provision of use, and finally, demolition of a skyscraper is immense. Therefore, when designing a tall building, one should seek rational and economical solutions that will increase the efficiency of this process and diminish its negative effects on the environment.

As energy consumption further increases with the height of the building, the tallest buildings in the world often contradict the promotion of an economical approach in the design of skyscrapers and, therefore, are certainly a contradiction of the idea of environmentally friendly design. The scale of European projects, which are generally not taller than 200 m, and often do not exceed 100 m in height, is more acceptable. In an interview, William Mitchell (Niederhoffer & Kenner, 2011) noted that the higher the building, the more floor space on subsequent floors must be allocated to construction and technical infrastructure. One always reaches a height at which adding the next floor ceases to have any justification except for ambition. In most European high-rise buildings, subsequent floors are justified in sufficiently large usable areas, which means that the associated energy consumption is also more justified.

The projects recommend the use of local and recycled materials (Finnigan, Gerardy, Popa, & Trabucco, 2019). Structural plans should be selected to ensure the effective use of materials and to reduce their use (Ali & Armstrong, 2010). Design effectiveness depends on, among others, the optimal dimensioning of elements that limit the bulk of the building, the use of prefabricated elements, and the variability of the load-bearing structure strength as a function of height. From a global perspective, energy consumption and the carbon footprint associated with the production of the materials used to build a high-rise building are also important. Therefore, research is being conducted into the more environmentally friendly production of traditionally used construction materials, concrete and steel (Finnigan, Gerardy, Popa & Trabucco, 2019; Law, 2021), as well as into the use of timber for the erection of high-rise buildings (Applegath, Veres, & Wu, 2021; Bahrami & Rashid, 2024).

In the design of tall buildings, it is also important to design durable, and at the same time multifunctional and flexible structures, that can easily be adapted or restructured to suit other functions in the future (Kashkooli, 2010; Gupta, 2012).

Ensuring the proper functioning of the building

Innovative technological solutions allow architects to plan how the buildings will function at the design stage. Accurate digital modelling permits us to simulate and programme the processes that will take place within the building (Robinson, 2007), test all available solutions, make informed decisions about the final shape of the building, and equip it with the necessary mechanical systems. It is possible to carry out, among

others, simulations of wind loads and natural ventilation, natural light and indoor shade, and thermal characteristics. It is also possible to carry out a comprehensive energy use simulation for the entire building, allowing the assessment of the building's performance and the comparison of costs of different energy-saving and carbon footprint strategies (Simmonds, 2005).

Today, the systems that consume the most energy over a building's life cycle are those systems that keep a building functioning: primarily ventilation, cooling and heating, but also artificial lighting, vertical transport, plumbing, computers and other equipment used by users. Although improvements in the efficiency of equipment and systems make the energy used to produce the embedded materials and erect the building increasingly important, its value is still secondary (Ali & Armstrong, 2010). While appropriate technical infrastructure is necessary, the goal is to reduce the amount of time when it is being used to a minimum.

Crucial are solutions introduced to ensure energy savings (Fig. 12) – reduction in energy losses and consumption – first of all: natural ventilation, passive and mixed cooling and heating systems, provision of night cooling, heat storage elements, heat recovery systems, increased insulation of the building envelope, protection against overheating of interiors, illumination with natural light, low-energy water systems, advanced zoned air-conditioning systems, and more efficient vertical transportation systems. It should be noted that elevators account for 2–10% of a building's energy consumption and during peak hours even for 40%. This is why the development of vertical transport technology is so important for the energy balance of a high-rise building. Recent advances in elevator technology help to implement many energy-saving solutions, even energy-generating elevators (Al-Kodmany, 2023b; Ali, Al-Kodmany & Armstrong, 2023).

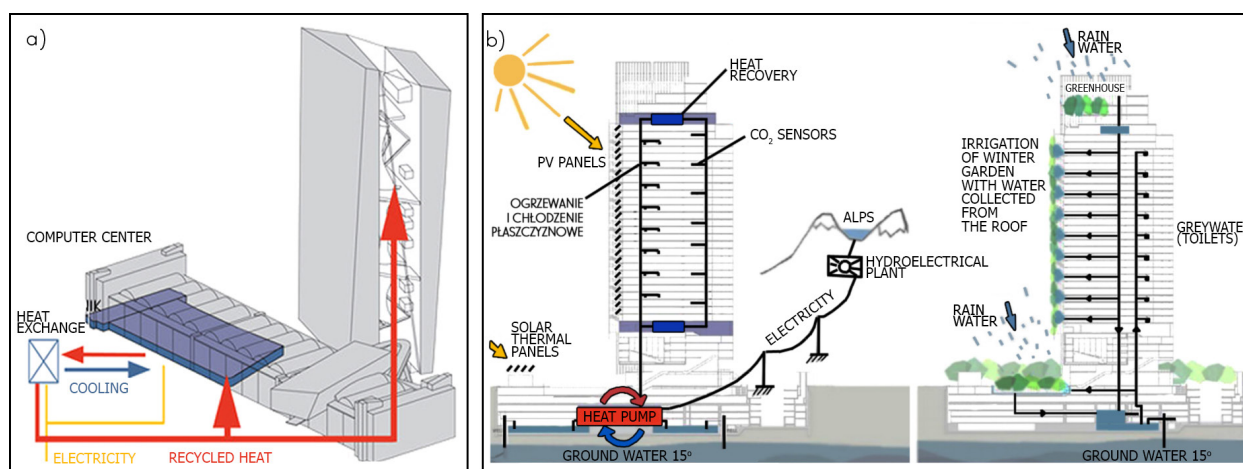


Fig. 12. High-tech solutions in high-rise buildings: a – ECB Tower, Frankfurt am Main, 2014: extracting heat from the computer centre; b – Grattacielo Intesa San Paolo, Turin, 2015: electricity from natural sources, HVAC system and installations – grey water and rainwater

Source: ^a© Coop Himmelb(l)au; ^bown elaboration based on: skyscrapercity.com [n.d.].

Tall buildings are also equipped with integrated building management systems (e.g. BMS), which control the other systems and elements of the building. Intelligent building management aims to reduce energy consumption (Kamal & Ahmed, 2023) by assessing the functioning of the entire structure, conducting diagnostics, and efficient detection of failures and breakdowns.

Energy from renewable sources

In architectural design, and nowadays also in the design of tall buildings, efforts are made to obtain energy from renewable sources (Imam & Kolarevic, 2018). However, the idea of a zero-energy tall building postulated in many projects (Ali & Al-Kodmany, 2012; Gupta, 2012) remains debatable (Pawłowski & Cała, 2013). Because of the large sizes and relatively small building areas, obtaining energy from renewable sources is a big challenge (Dalton & John, 2008), but ongoing research may indicate that there is great potential for solar and wind power (Land, 2008; Vita, ŠarkiĆ-Glumac, Hemida, Salvadori & Baniotopoulos, 2020; Kim & Im, 2021).

The provision of biomass makes the operation of the building dependent on a complex supply chain. Heat pumps, on the one hand, can only be implemented in a building located on large plots of land, but on the other hand, can be installed in the ground surrounding the underground parts of a high-rise building. Interesting solutions are also emerging, based for example on heat recovery from large server rooms or data centres (Fig. 12a).

Solar energy can be used passively or actively. Direct solar gain – the heating of spaces adjacent to the façade and the use of thermal storage mass from the building's elements are usually undesirable due to the priority of preventing overheating and even the need for cooling. In addition, the weight of materials that accumulate thermal energy well is a significant factor in structure design (Lotfabadi, 2015). However, thermal energy storage can be taken into account if the building structure is designed with reinforced concrete. Passive systems are usually based on indirect gains – through the design of large-scale greenhouse structures (atria, winter gardens) or double glass façades, and heat is extracted and used to support heating systems and stimulate air circulation.

Active solar design is associated with the use of collectors or photovoltaic panels. The location of solar thermal collectors is generally limited to roof planes so that the transmission path of the medium to the lower floors is greatly extended, reducing the efficiency of the system (Marchwiński & Ruchała, 2015). In addition, there is a much greater need for cooling than for hot water in a high-rise building. The use of photovoltaic systems has much greater potential. A building can be equipped with photovoltaic roof panels, as well as a system of façade cladding or shading panels with PV cells and even photovoltaic glass. However, the roof area of a tall building is relatively small and is often used for representative rather than technical functions. The shape of the plot determines how much of the façade area is insulated, and the surrounding buildings can shade a significant part of the building. The integration of façade elements with PV cells results in interior shading, which can be disadvantageous or have positive effects, but only in summer, which is why such solutions are usually only used in windowless zones or for technical rooms (Marchwiński & Ruchała, 2015). Furthermore, photovoltaic panels in Europe should be sloped rather than fixed on flat walls or roofs, so few buildings have planes that allow their effective use (Fig. 13a). However, the use of shading shelves with PV modules on the upper floors significantly reduces the wind loads. Furthermore, panel production requires a huge amount of energy, and there is still no way to recycle them effectively.

Descriptions of using wind turbines with horizontal axes of rotation in tall buildings regularly appear in the literature (Johnson, 2014), but they only appear in experimental designs (Fig. 13b). Large wind turbines with horizontal axes of rotation require a certain wind speed blowing from a certain direction. However, in a dense and, moreover, time-varying urban environment, it is impossible to unambiguously define wind directions (Zielonko-Jung, 2013). The shape of the plot of land may also influence the form of the building and the possibility of locating a building-integrated turbine directed towards the prevailing wind direction. In addition, large turbines generate dynamic loads (which are particularly dangerous in the case of several turbines whose operation is synchronised), the impact of which has to be estimated and neutralised.



Fig. 13. Obtaining energy from natural resources: a – Tribunal de Paris, Paris, 2017 – inclined panels with PV cells; b – Strata building, London, 2010 – integrated wind turbines

Source: ^aSergio Grazia 2017; ^bColin 2014.



Fig. 14. Buildings which underwent façade replacement or reconstruction in the 1990s: a – Intraco I, Warsaw – façade replacement in 1998; b – CityPoint, London – alteration, 2000

Source: ^aAstrorek [n.d.]; ^bStoneColdCrazy 2007.

This can be a very difficult, time- and cost-consuming task due to the difficult-to-define range of wind impacts. In addition, the movement of the large turbines and the vibration of their structural components and the building generates noise that negatively affects users (Al-Kodmany, Ali & Armstrong, 2023). However, the use of turbines with a vertical axis of rotation is becoming increasingly popular. They are smaller and less efficient but can be located on the roof of an elevated building as one of the additional elements of its technical equipment, thus not being a limitation in the shape of the building (Marchwiński & Ruchala, 2015). The use of such a solution significantly reduces vibration and noise, and the turbines can be operated in winds blowing from different directions.

Redevelop, do not demolish

In cities where tall buildings have been built since the 1960s, as early as the 1990s, it proved necessary to adapt them to new utilitarian and aesthetic requirements (Fig. 14), as well as the requisite levels of energy saving (Ysebrant & Zielonka, 2008). The problem of adapting buildings to the changing standards has intensified in the 21st century and will be an increasingly common phenomenon. A design approach in line with sustainable development guidelines requires the renovation of an existing building, and the preservation of as many elements of the existing building as possible: the entire structure, the core, the foundations or at least, for example, gypsum boards from the old building (CTBUH Staff, 2021). Demolition leads to large time and money expenses, as well as huge energy consumption and the creation of waste (Scheublin, 2008). Therefore, the redevelopment of an existing building, combined with an upgrade of its standard, changing the façade, form or even height, is preferred (Rees et al., 2013).

In densely built-up cities, tall building construction is often preceded by the demolition of an existing but significantly lower building. Such decisions have necessitated the realisation of almost all newly

constructed high-rise buildings in Frankfurt and central London. The authorities in the latter city have a policy of encouraging the erection of skyscrapers in designated locations and the demolition of 1960s buildings of unsatisfactory quality (Binder, 2006). A skyscraper, The Shard, has even been built on the site of a 100-metre building. Demolitions are also taking place in Warsaw. However, a sustainable design approach rather requires the renovation of an old building (Rees et al., 2013). Therefore, new developments in cities such as Paris, Frankfurt, Moscow, Brussels, Warsaw, Belgrade, and London do not always involve an expansion of tall buildings but only a change in their standard, appearance and even height.

Therefore, when it comes to newly designed buildings, the need to take into account possible future transformations and changes to their functions, as well as the question of demolition and subsequent recycling of embedded materials (Gupta, 2012), are strongly emphasised. Tall buildings are more and more often designed as multifunctional and flexible so that they can be adapted to the changing requirements of the market and users without the need for refurbishment (Kashkooli, 2010). The renovations carried out usually involve the replacement of all elements of a high-rise building except the core structure. Its adaptability to new conditions becomes crucial to the perception of the building as environmentally friendly (Rees, 2008). Most importantly, maximum flexibility of space limited by structural elements should be ensured, enabling the building to be adapted to new standards and functions by simply replacing the installation and finish (Rees et al., 2013).

SUMMARY

High-rise buildings are justified in the largest cities, where their introduction will prevent urban sprawl. In Europe, only a few cities have reached the size of a metropolis, but it is in these areas that high-rise buildings are being built. The pursuit of reducing urban sprawl and preserving energy used for transporting people and goods leads to planning cities with a higher building intensity. This can be achieved, among others, through the concentration of tall buildings. The erection of tall buildings is also justified in cities lacking land for new property development.

The height of European tall buildings is limited, with almost no buildings higher than 300 m and most of the continent's outstanding developments not exceeding 200 m. The height limitation is a great advantage, as the buildings realised are not just a display of ambition and unjustified excessive material and energy expenditure. The heights and usable floor areas of buildings are justified by functional needs.

Since the 1990s, European tall building designers have been increasingly focused on operating in line with natural conditions and respect for ecological values. Further development of these trends can be anticipated. Contemporary projects demonstrate a new approach to tall buildings: as consumers of natural resources, they are transformed into structures that are intended to function in accordance with the laws of nature and the norms of sustainable development.

As the greatest energy consumption is related to the functioning of installations ensuring the correct parameters of the interior microclimate, the basic action becomes limiting their use through the design of the building and the use of natural processes. Compared with some other climatic zones, European high-rise buildings may require higher energy expenditure for the mechanical systems, ensuring the comfort of users. However, climate constraints are objective factors, and the rational approach to designing European high-rise buildings is to maximise the use of passive solutions and reduce the operating time of mechanical systems. In order to do so, the latest technologies are used to create an efficient design for both the building form and modern high-efficiency installation solutions.

There is a trend towards the use of advanced computer technology at all stages of the design process to analyse local conditions, for generative design and the modelling of more complex geometric structures, as well as to analyse the subsequent functioning of the building (particularly in terms of energy efficiency

and creating high user comfort). Thanks to innovative technologies related to the design process, the form and façades of tall buildings are shaped in accordance with the local microclimate. As a result of correctly shaping the form and façade of the building, as well as taking advantage of naturally occurring processes, it is possible to limit the use of devices and systems that ensure the suitable microclimate of the interior.

Currently, all skyscrapers being built in Europe are equipped with a number of installations from a group of advanced technologies – these increasingly efficient systems consume less energy, as well as allow for energy to be recovered. Integrated building management systems control the mode and time of operation of other systems, limiting the energy consumption needed for their operation. In subsequent projects, effective methods of obtaining energy from renewable sources are sought. None of the sources of renewable energy are yet being used effectively in high-rise buildings, but ongoing research may indicate that there is great potential for solar (especially indirect passive gains and PV panels) and wind power (rather small turbines with a vertical axis of rotation).

As high-rise buildings have been constructed in Europe for more than 70 years, the continent's approach to ageing high-rise buildings can serve as a guideline for designers in other parts of the world. Design issues are now being considered in relation to the entire life cycle of the building.

CONCLUSIONS

The outcomes of the literature review described in this paper allow the conclusion that tall buildings in Europe are becoming more and more sustainable, and the idea of sustainable development is applied to the entire life cycle of a skyscraper. The conducted analyses confirm the hypothesis that the European approach can be the basis for general guidelines for the construction of green tall buildings. They all need to go through a holistic design process aimed at not just achieving certification but also planning the whole building's life cycle.

Skyscrapers should only be built in large cities, where there is a need for a large amount of new floor space and it is not possible to enlarge these cities or increase their area, which could lead to the urban sprawl phenomenon.

The global race to the skies should be limited so that the gains from floor space in high-rise buildings compensate for the consumption of the energy and the materials used in their construction and later building operation.

In some climates, buildings cannot operate primarily on the basis of appropriate form, façade design and passive phenomena. However, irrespective of the climate, the aim should be to reduce the operating time of mechanical systems as much as possible, using a bioclimatic design approach.

The installation solutions designed for tall buildings should be based on the latest technological developments – e.g. advanced, energy-saving technological solutions, highly efficient equipment, and energy recovery systems.

The use of available local and recycled materials and renewable energy sources should also be considered. In tall buildings, photovoltaic panels and wind turbines can be of particular importance, and their use should be further researched and developed.

The tall buildings have to be designed including future changes in function, technical infrastructure, façade and even the addition of further floors. It must not be assumed that the building will be demolished if any change is necessary.

Thanks to computer simulations and analyses, the building's future performance should be checked during the design stage, and what spatial form shaping and choice of infrastructure is optimal in terms of reducing energy consumption and carbon footprint.

It is impossible to say whether high-rise buildings will ever reach the level of zero-energy buildings, but by analysing the European approach to their design, it is possible to formulate guidelines that will help to construct buildings that result in significantly lower energy consumption.

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MOŻLIWOŚCI WZNOSZENIA BUDYNKÓW WYSOKICH I PROEKOLOGICZNYCH – OCENA Z PERSPEKTYWY EUROPEJSKIEJ

STRESZCZENIE

Celem artykułu jest odpowiedź na pytanie, czy budynek wysoki w całym swoim cyklu życia może być ekologiczny. Zaprezentowano syntetyczne wyniki przeglądu literatury oraz stron internetowych dotyczących aspektów proekologicznych w projektowaniu wieżowców. Potwierdzona została hipoteza, że europejskie podejście do projektowania wieżowców uwzględnia aspekty rozwoju zrównoważonego i może być podstawą ogólnych wytycznych do projektowania „zielonych” budynków wysokich. Przede wszystkim w przypadku europejskich realizacji lokalizacje, powierzchnie i wysokości są uzasadnione funkcjonalnie. Ponadto, pomimo wymagającego klimatu, wieżowce projektowane są z wykorzystaniem rozwiązań bioklimatycznych oraz z uwzględnieniem wykorzystania zjawisk pasywnych i skrócenia czasu pracy systemów mechanicznej wentylacji i ogrzewania. Niezbędna infrastruktura techniczna wykorzystuje wysokosprawne, energooszczędne urządzenia i rozwiązania. Pozyskiwanie energii ze źródeł odnawialnych jest obecne, choć mało popularne – technologie te wciąż się rozwijają i zyskują na znaczeniu.

Słowa kluczowe: budynki wysokie, wieżowce, zielone miasto, ekologia, rozwój zrównoważony

PROMOTING ENVIRONMENTAL SUSTAINABILITY IN CONSTRUCTION: EXPLORING IMPLEMENTED SOLUTIONS THROUGH CASE STUDIES

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ABSTRACT

It is imperative to take pro-ecological actions that are beneficial to health, as well as adopt sustainable development practices in the face of the current environmental challenges facing humanity. It is crucial that environmental protection is implemented by all people on Earth, because the future is worrying – especially for what will be left for future generations. Green building solutions are being implemented worldwide, but not always in an appropriate manner. All green architecture integrates sustainable development and conservation, regardless of location. This article summarises and characterises the concept of the 6E (economic, energy-efficient, ecological, elastic, aesthetic, ergonomic) ecological building concept and the 3R (reduce, reuse, recycle) principle. It also presents an analysis of two ecological buildings in Poland. The first is a wooden building located in the village of Podgać, which serves as an example of combining modern design and ecology. It was built in harmony with nature and blends in with the natural environment of the forest. A half-timbered house in the village of Jarzębia Łąka is the second example where traditional construction, modern technical solutions and environmental protection come together. The presented project examples were examined in terms of ecological building principles and then compared with the 6E concept and the 3R principle. This paper presents a comprehensive study of two distinct eco-friendly building structures. The investigation covers technical characterisation, compliance with the 6E concept, comparison of ecological efficiency, and conclusions with recommendations. The Dom Baby Jagi [Baba Jaga House] in the village Podgać showcases a harmonious blend of simplicity, functionality, and economy, utilising wood with insulation for year-round habitation. It integrates renewable energy sources and rainwater harvesting, contributing to its ecological sustainability. Meanwhile, the half-timbered building in Jarzębia Łąka employs clay-straw bricks for construction, emphasising economic and environmental benefits with vapour-permeable walls and efficient insulation. Both structures exemplify ergonomic design, eco-friendly construction practices, and aesthetic integration with their natural surroundings. These findings underscore the importance of incorporating environmentally conscious solutions in modern architecture to address contemporary environmental challenges and promote sustainable development.

Keywords: eco-friendly construction, sustainable development practices, green building solutions, 6E concept, 3R principle

INTRODUCTION

The subject of ecological construction is multifaceted and encompasses various dimensions. The term ‘green building’ refers to structures made from healthy and energy-efficient materials and solutions, employing energy-efficient and environmentally non-destructive construction methods and techniques. Such construction is more integrated with nature and significantly less polluting to the natural environment compared to conventional buildings (Walenda & Starczyk-Kołbyk, 2022).

The 6E concept is based on the idea of increased energy efficiency in construction. Nowadays, there is a growing interest in the energy industry and academia to apply advanced energy, exergy, exergo-economy, exergo-environment, emergo-economy and emergo-environmental analyses – ranging from 3R to 6E analyses – to achieve better solutions (Khani, Manesh & Onishi, 2023). This concept involves the design and construction of buildings with the aim of minimising energy consumption and reducing negative environmental impact (Şahin & Kılıç, 2024). It encompasses all aspects of the building, including energy efficiency, construction and operational costs, a sustainable approach to the natural environment, user comfort, and architectural aesthetics (Fig. 1). The 6E concept encompasses six key aspects:

- (i) Economic – ensuring that the project and construction are achievable within the available budget, while reducing long-term operating costs.
- (ii) Energy efficient – ensuring efficient use of energy during construction and operation of the building, including strategies for insulation, ventilation, lighting and heating systems.
- (iii) Ecological – minimising the building’s impact on the natural environment by using ecological materials, reducing carbon dioxide emissions, conserving natural resources, and protecting local ecosystems.
- (iv) Elastic – using prefabricated and other ready-made components, ensuring modularity.
- (v) Aesthetic – addressing the design and finishing aspects of the building to create an attractive and harmonious environment that is pleasing to the eye and in keeping with its surroundings.
- (vi) Ergonomic – providing comfort and functionality for users through ergonomics, accessibility for people with disabilities, and efficient use of space.

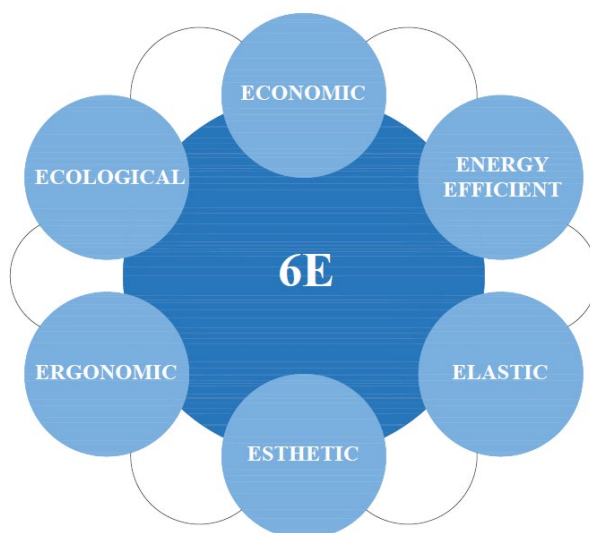


Fig. 1. Schematic representation of the 6E concept

Source: own work.

The 3R principle (reduce, reuse and recycle), also known as the “waste management hierarchy” (Coalition of 5 Fractions, 2022), is in perfect alignment with ecological construction (Zhang et al., 2022; Vaverková, Matsui & Vaverka, 2023; Victar, Perera, Palihakkara & Dewagod, 2023). Reduce, reuse, and recycle, are three components of the components of the 3R concept. Reduce means selecting and using factors that reduce the amount of the waste produced. Recycle means using waste as a resource. Reuse means using waste that is still in a usable condition. Reduce is the most important factor compared to reuse and recycle for minimising waste (Aadal, Rad, Fard, Sabet & Harirchian, 2013). Waste reduction through the 3Rs is one of the most effective steps the construction industry can take toward sustainable waste management (Mitra & Datta, 2014). When reuse and recycle practices are applied to the large amount of construction waste generated at construction sites, such practices lead to the achievement of sustainable development goals and often to the development of new products (Schroeder, Anggraeni & Weber, 2019).

As Skowroński observed in the latter half of the 20th century, a waste management system was developed, which is simplified and based on the 3R principle: reduce, reuse, and recycle (Fig. 2). The objective is to halt further environmental degradation (Skowroński, 2015). When purchasing building materials, it is important to choose wisely and buy only the necessary amount, avoiding unnecessary purchases. The reduce principle necessitates that packaging be biodegradable. During the construction phase and throughout the operational lifespan of the building, it is encouraged to exercise creativity in identifying potential reuse opportunities for materials. Recycle, the final stage of the 3R principle, involves the segregation of waste during construction and building use, allowing for the recycling of materials into new products. To preserve and improve environmental quality, protect human health, and ensure the prudent, efficient, and rational use of natural resources, environmentally friendly actions are already being taken with the aim of saving our environment (Ulewicz, 2021).

The US Census Bureau (2024) indicates that the global population has surpassed 8 billion individuals on 15 November 2023. The global population has been steadily increasing since the end of World War II (Ganivet, 2020; Vollset et al., 2020). Projections suggest that this upward trend will continue, and it can



Fig. 2. Schematic representation of the 3R principle

Source: own work.

be reasonably assumed that there will also be an increasing demand for housing. Construction, in conjunction with the production of building materials, exerts a profound influence on the natural environment (Maraveas, 2020; Tang, Li, Tam & Xue, 2020). The expansion of the global population has intensified the urgency for environmental stewardship among humanity. Developers with a long-term perspective should prioritise ecological solutions for all aspects of construction and subsequent building operations (Kang, Zhang, Zhu & Zhang, 2021; Sood, Kumar, Jena & Joshi, 2023). Such action helps to reduce, among other things, the emission of carbon dioxide into the atmosphere.

The term ecological construction is a broad concept that encompasses various technologies and building materials. Among the eco-friendly materials used in construction are: (i) natural materials, including clay, sand, stone, rocks, straw, hay, flax, hemp, and wood, are employed in the construction industry; (ii) ceramic materials, such as bricks and expanded clay aggregate, are also utilised; (iii) concrete materials, including cellular concrete, are also used; (iv) synthetic materials, such as silicates, are also employed in the construction industry; additionally, (v) glass and organic materials, including wastepaper and fibres derived from it (Kietliński, 2015; Silva, Kim, Aguilar & Nakamatsu, 2020; Sharma, 2020; Amran et al., 2021).

The objective of this article is to conduct a comparative analysis of two distinct ecological buildings in terms of their compliance with the principles of ecological construction, with a particular focus on the 6E concept and the 3R principle.

MATERIAL AND METHODS

The study focused on two different building structures: (i) a wooden structure located in the village of Podgać, and (ii) a straw and clay half-timbered structure located in the village of Jarzębia Łąka.

The investigation included several key areas:

- (i) Technical characterisation: This included detailed descriptions of the structure, building materials, and construction technologies used in both buildings. The wooden building in Podgać and the half-timbered building in Jarzębia Łąka were examined for their architectural features, material compositions, and construction methods.
- (ii) Conformity assessment: The study analysed the extent to which the surveyed buildings complied with the principles of the 6E concept, which includes energy efficiency, ecological use of materials and technologies, structural adaptability, architectural aesthetics, ergonomic design, and economic viability. In addition, the evaluation included an assessment of how well the buildings complied with the 3R principle of the waste management hierarchy, focusing on reduction, reuse and recycling practices.
- (iii) Comparison of environmental performance: A comprehensive comparison of the environmental performance of the buildings was conducted, evaluating factors such as energy consumption, carbon dioxide emissions, waste generation, and other relevant environmental indicators. This comparative analysis provided insights into the overall environmental efficiency of each building.
- (iv) Conclusions and recommendations: Based on the results of the analysis, conclusions were drawn regarding the environmental performance and overall sustainability of the buildings studied. In addition, recommendations were proposed to improve their environmental performance and optimise their environmental impact.

RESULTS AND DISCUSSION

There is a noticeable shift in modern construction practices towards the comprehensive integration of ergonomic principles at every stage of the building lifecycle, from initial design and construction to ongoing operation and maintenance (Awad, Guardiola & Fraíz, 2021; Sutarja & Putra, 2022). This multifaceted approach not only

emphasises the importance of creating spaces that optimise comfort and functionality, but also underscores the importance of prioritising the safety and well-being of both construction workers and eventual occupants (Becerik-Gerber et al., 2022; Engelen, Rahmann & de Jong, 2022). By carefully considering ergonomic factors throughout the planning and execution phases of a construction project, stakeholders can proactively address potential challenges and mitigate risks associated with physical strain, injury or discomfort (Riva, Rebecchi, Capolongo & Gola, 2022). In addition, the seamless incorporation of ergonomic design elements contributes to increased productivity, efficiency, and overall user satisfaction, thereby fostering a conducive environment for work, leisure, and daily activities within the built environment. As such, the overarching goal of integrating ergonomic solutions into contemporary building endeavours transcends mere compliance with regulatory standards; rather, it epitomises a commitment to fostering sustainable, human-centred spaces that promote optimal performance and well-being for all stakeholders.

Baba Jaga House

The initial example under consideration is a wooden structure situated in the Podgać region, surrounded by a pine-birch forest (Fig. 3). The image of the wooden building in the Podgać village illustrates the symbiotic relationship between the structure and its natural surroundings. The case study concerns a modest dwelling, covering a mere 35 m² of building area, yet the available space has been optimally utilised.

Dom Baby Jagi [Baba Jaga House], designed by the Polish architectural firm Pole Architekci, exemplifies a harmonious integration of simplicity, functionality, and economy. The building is supported by nine concrete foundation columns and offers a living space of 35 m². The use of wood with insulation allows for year-round habitation. Its unconventional roof shape gives it a modern character, while the glass façade opens onto

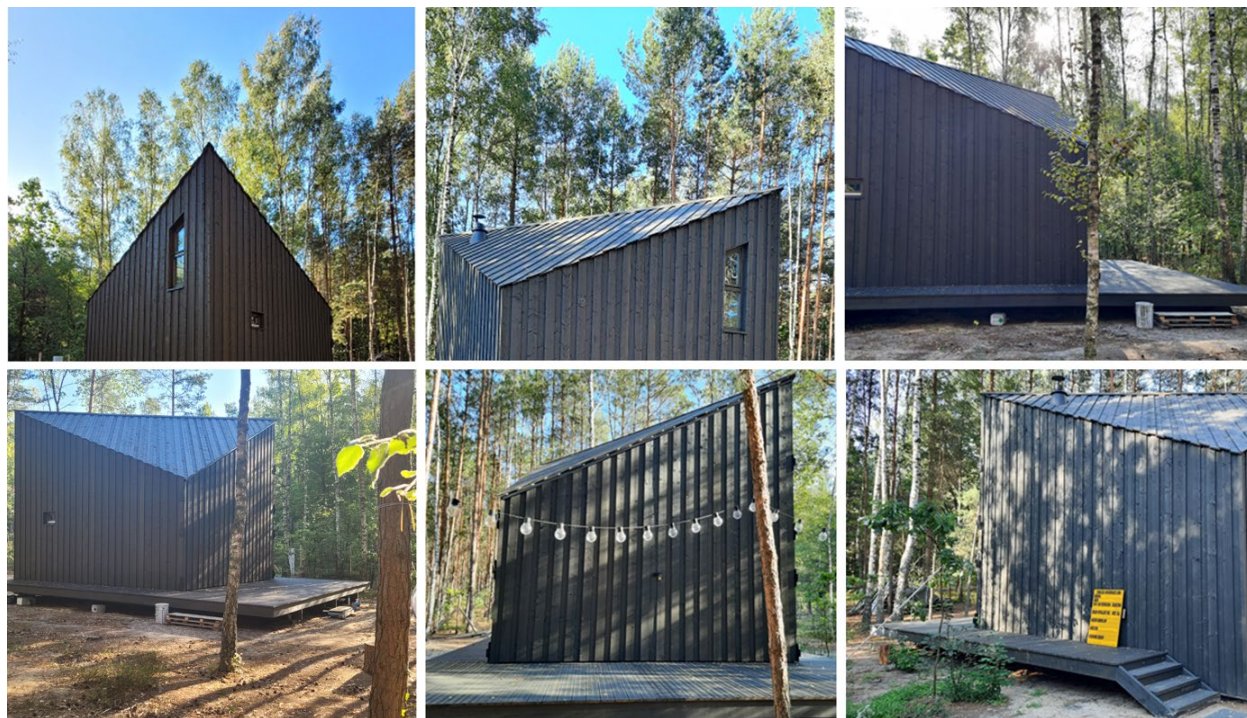


Fig. 3. View of the façade of a wooden building in Podgać, Poland

Source: photos by Aneta Czachowicz 2023.

a terrace. During the owner's absence, the glass walls are secured with gates spanning the entire height of the building, which adapt to the user's needs. Furthermore, the external finish can be altered according to local regulations and aesthetic preferences.

From an economic standpoint, it is crucial to utilise appropriate construction materials, such as wood instead of plastics, and windows with superior thermal performance. The high-quality wooden planks employed in the construction of the terrace in Podgać exemplify an aesthetic appeal that is also characterised by durability. The modular construction method allows for the rapid erection of buildings, while the use of high-quality materials ensures cost-effectiveness. The incorporation of renewable energy sources, such as photovoltaic panels, reduces the associated costs of electricity. The compact dimensions of Dom Baby Jagi result in reduced construction and maintenance costs.

The rising costs of energy have prompted developers to seek ways to reduce their expenditure by installing devices powered by renewable energy sources or constructing energy-efficient homes. The examined building is a simple, compact rectangle, which reduces operating costs. The entrance is located at the front, and the wooden window provides natural lighting to the living room and loft. Wooden gates protect the entrance and insulate against the cold. The gabled roof minimises heat loss and costs. Wooden houses are well-insulated, reducing operational costs. The adaptation includes the optimal utilisation of photovoltaic panels and sunlight, which provides more daylight during the day and better insulation at night.

From an ecological perspective, the discussed building exemplifies the principles of sustainable construction. During both the design and construction phases, environmentally conscious materials were utilised, and meticulous attention was paid to ensure a healthy indoor microclimate and enhance the productivity of residents (JWA, 2023). Another noteworthy aspect of the project in Podgać is the incorporation of a rainwater tank. This solution allows for a reduction in the use of tap water, with additional benefits including the softness of water, low chlorine levels, and high nutrient content in rainwater compared to tap water (Rolmarket.pl, 2019). The property also benefits from its location in the heart of the forest, which results in lower temperatures during the summer by several degrees compared to urban areas, while in winter, some of the flora shields the building from the wind. Trees not only provide shade but also, by their nature, allow for breathing in clean air. The use of photovoltaic panels makes the facility not only economical and energy-efficient but also ecological. By reducing electricity consumption from the grid, which is generated primarily from coal combustion in Poland, the facility is contributing to the reduction of greenhouse gases. Figure 4 illustrates the structure of electricity production in Poland.

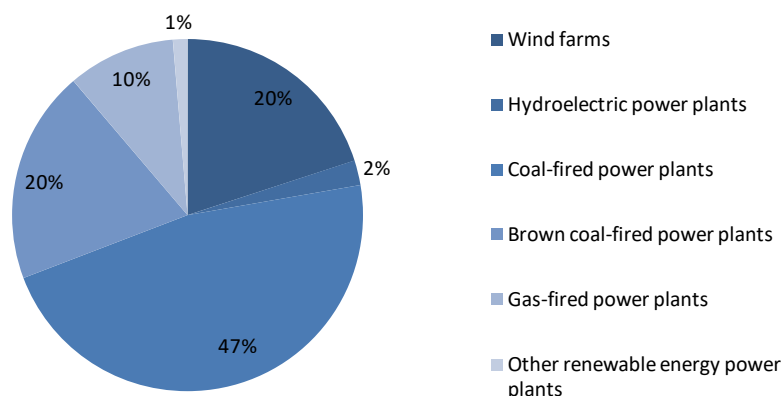


Fig. 4. Structure of electricity production in Poland in December 2023

Source: own work.

The recreational cottage, designated as Dom Baby Jagi, is a simple, ergonomic rectangular structure. It comprises a living room, kitchen, dining area, bathroom, and a loft bedroom that overlooks the forest. Its straightforward design enables various configurations and year-round utilisation, thanks to its wooden construction with insulation. There are three variants (models A, B, C) available, which can be modified to align with the developer's preferences and site conditions. The utilisation of prefabricated modular elements enables the circumvention of the 'construction season' and the reduction of costs.

Modern construction is characterised by simplicity, ecology, and the efficient use of materials and space. The examined building exemplifies these characteristics, integrating aesthetics, solidity, and functionality. Designers and developers endeavoured to adapt the project to the surroundings by choosing a simple form and a wooden façade, which allows the building to harmoniously blend into the landscape. Efforts were made to minimise tree cutting and comply with the provisions of the building conditions decision, which is crucial for the development area. The absence of artificial pavements and the use of natural materials such as wood further enhance the aesthetic appeal of the surroundings. Such harmony with nature positively affects the well-being of the residents, creating an atmosphere of tranquillity and harmony.

The discussed small house has been optimally utilised, accommodating a living room with a kitchenette, a bathroom, and a bedroom on the mezzanine. Despite its small size, each room has all the necessary elements. The compact bathroom (2.3 m²) limits space for residents, although it features a shower instead of a bathtub to save space. The mezzanine has been incorporated in an unconventional way for small buildings, although the stairs leading to the bedroom are narrow and steep, replacing a ladder. The living room with a kitchen is the largest room (23.6 m²), allowing free movement without corridors, and ergonomically designed walls have recesses for cabinets. The roof enables the installation of photovoltaic panels or solar collectors, saving space on the plot and utilising ecological solutions.

The principle of reduction is applicable to various elements and aspects of the construction process, commencing with the planning of the building on the plot, continuing through its construction, and concluding with its use. The reduction of waste in this project commenced during the design phase. Due to the attractiveness and aesthetic qualities of the plot, it was determined that the project would be of a modest size but would possess all the necessary features of a year-round home. Proper quantification allows for waste reduction, its proper management, and planning of necessary materials, deliveries, and construction equipment. An important aspect is also adapting the technology, location, and shape of the building to the site. In the discussed example, the building was designed in such a way that photovoltaic panels could be installed on the roof, or a heat pump could be used. Additionally, the house was rotated to the east by 18° to optimise the sunlight exposure of the roof and façade. This action helps to reduce heat loss and to maximise the use of panels on the roof. The technology used to construct the house in Podgać is relatively fast to implement. The building was not constructed on-site; ready-made elements made of prefabricated wooden technology, which minimises waste and enables their proper management due to their further processing at the factory, were transported to the construction site and then assembled into the complete structure. This solution also features a quicker implementation time than traditional construction. Moreover, during the construction process, the construction team utilised energy-efficient equipment, and any unused materials were returned to the store for reuse in another construction project. In the operational phase of the facility, devices and household appliances were also selected for their energy efficiency.

The term reuse refers to the reuse of materials, and in the context of the discussed topic, it signifies the conscious utilisation of equipment and building materials, thereby saving natural resources. The technology of wooden houses is environmentally friendly because, after tree felling for construction purposes, new plantings are carried out. This practice ensures that the number of forests does not decrease and provides new material for the future. Furthermore, the process of growing trees does not require energy, and the plants themselves absorb large amounts of carbon dioxide. In the construction of the building, concrete technology

was employed solely for the purpose of erecting the foundation footings, which were constructed using reusable formwork that will be utilised for future projects. The remainder of the structure is based on a wooden frame. Another significant factor for developers was the utilisation of restored old furniture that was destined for disposal, as well as the aforementioned rainwater tank.

The final principle of the 3Rs is recycling. The structure of the Dom Baby Jagi can be dismantled with relative ease. Once this procedure is complete, the area can be restored to its original state with minimal delay. The wooden materials that comprise the structure can be reused, and any surplus can be used as fuel. During the process of tree growth, stored carbon dioxide is released again, closing the carbon dioxide cycle. Furthermore, in the event of a potential relocation, individual elements are disconnected, transported to a new location with the prepared ground, and finally, the wooden structure is reassembled. The use of wooden prefabricated elements has resulted in the collection of any wood waste at the sawmill, where it undergoes further processing and is used for other purposes.

Half-timbered building in Jarzębia Łąka

Another example of an ecological building is a house constructed from clay-straw bricks. The house in question was constructed using an economic system (Fig. 5). The clear advantages of the property are its ecological and health-related aspects. The house aesthetically blends in with the surrounding pine forest. It is a standalone building without a basement. The main building materials are wood, clay, and rye straw. The final material, rye straw, must be of good quality, precisely threshed, and weed-free. Otherwise, grains and other seeds could sprout. The straw used during construction was seasoned and consists only of woody stems, providing better protection against rot. An essential factor during construction was the proper scheduling of construction and assembly work, just like in the case of the Dom Baby Jagi. The house was erected on concrete foundations, and then the wooden frame was assembled. In the final stage of construction, the roof is covered to protect the walls from rainwater. The empty spaces between the wooden frame were filled with clay-straw bricks, taking into account fire safety concerns. Subsequent stages of construction were similar to standard builds, involving the construction of partition walls, plastering, façade work, carpentry, long-term roof covering, and installation distribution.

The building was constructed on a less expensive rural property but has good railway connections to Warsaw. Furthermore, construction materials were used that maintain their properties over a longer period of use. In the described half-timbered building, bricks made of weed-free and mould-resistant straw, as well as clay treated with antifungal agents, were used. Additionally, the straw in the bricks was arranged to achieve the best insulation. The lowest heat transfer coefficient observed during testing was $0.073 \text{ W} \cdot \text{mK}^{-1}$ for a wall thickness of 40–45 cm (Podwysocka, 2017). The use of straw from an economic system resulted in a notable reduction in construction costs for the building. The analysed building was designed to be easily constructed and to have an interior design that utilised a gabled roof and a simple, functional gable shape (Malińska, 2022). These factors indicate a reduction in costs from the design stage through construction to operation.

One of the key advantages of the project in question is the reduction in operating costs, which can be attributed to the simplicity of the building's structure and its location on the plot. The roof, with a 30-degree slope, is insulated with 30-centimetre thick mineral wool. Furthermore, the building's orientation allows for the installation of photovoltaic panels on the southern-facing roof plane, which enables the maximum utilisation of the devices and, thus, their unparalleled electricity production. The electricity generated in this way will be used to heat the building and domestic hot water. Additionally, the applied technology has resulted in vapour-permeable walls (Podwysocka, 2017), without incurring additional costs. Furthermore, the house is located in the vicinity of forests. This is a measure that enhances not only the aesthetic and visual qualities but also the economic ones. The building is significantly protected from winds, thereby reducing the demand for electricity to heat the house.



Fig. 5. A view of the half-timbered building in Jarzębia Łąka, Poland

Source: photos by Aneta Czachowicz 2023.

One of the most crucial aspects of any construction technology is its environmental impact. This technology aligns with the principles of sustainable construction, as evidenced by its ability to create a healthy microclimate, construct buildings in a manner that respects the natural environment, and avoid the use of chemical compounds that may cause allergies (Podwysocka, 2017). Furthermore, in the case under study, natural agents were used for impregnation, namely building lime. This type of lime is recommended for more humid spaces because it possesses antifungal, antiseptic, and antibacterial properties (Balcerowska, 2020). It is also worth mentioning the previously cited heating system, which will utilise green photovoltaic energy, as well as the rainwater tank, from which water will be used for gardening purposes (Malińska, 2022).

The single-family residential building is a detached, single-storey structure with a partially usable attic and no basement. It comprises one bedroom, a living room with a kitchenette, a bathroom, a utility room, and a study. The half-timbered house is distinguished by its functional structure and rectangular shape. The simplicity of its design allows for a wide range of design possibilities. The flexibility of the examined construction is evident in the variety of finishing options available. The developer selected the most environmentally friendly solution, which involved the use of external and internal plaster made of clay, whitened with natural lime. However, this was not the only option available, as there was also the possibility of using natural cladding boards for the façade.

The principles of the 6Es encompass not only functional and environmentally friendly considerations but also aesthetic concerns. In the case under study, the plot for construction was carefully selected to create a healthy microclimate with the surrounding nature and to minimise the impact of the development on the environment. The building was designed to preserve the bordering trees and to provide views of the forest from the windows. The plot is located at the last line of development before the forest. The building's distinctive appearance is derived from the use of natural and minimally processed materials, including

wood, straw, and clay, in its construction. These materials contribute to the building's visual distinction from the ubiquitous concrete structures that are prevalent in urban areas. The simplicity of the colour scheme and technology employed in the design of half-timbered houses, which originated in rural Poland, is evident in the building's design. The integration of the building into its surrounding environment, evoking images that many people may recall from their childhood, is another factor that contributes to the building's aesthetic appeal. The strategic placement of windows not only allows for the illumination of rooms but also enables the observation of picturesque views. These features contribute to the building's seamless integration with its natural surroundings. The project demonstrates that eco-friendly construction is not incompatible with modernity or functionality and can be aesthetically pleasing at the same time.

The selection of the described half-timbered house technology in wooden construction with the infilling of clay-straw blocks is in accordance with the principle of ergonomics. The building combines the comfort of use in a space made from natural materials. Surrounding the building is nature in the form of forests and meadows. Due to its simple construction and the limited number of internal walls, there is greater flexibility in adapting the rooms to the user's needs and comfort. The building contains all the necessary facilities and rooms for human habitation. It is usable year-round, providing coolness in the summer and effectively retaining warmth in the winter. In addition to the previously mentioned solar panels installed on the roof, an ecological cesspool was also constructed, which, besides its benefits to nature, facilitates the use of the property by reducing the frequency of tank emptying. The building's convenient two-flight, broken stairs with a landing connect the ground floor with the attic, enhancing internal accessibility. Its construction and execution methods are unconventional in comparison to modern standards, but just a few hundred years ago, they were popular and widely used. The building was primarily created as a place to live and spend leisure time surrounded by nature.

Ecological construction is closely related to reducing the generation of waste during construction, minimising resource wastage, and opting for environmentally friendly products in biodegradable packaging. It is important to note that, like any other construction project, waste is generated during the building process, but this is mostly organic waste. The majority of these leftovers can be collected as compost, including wood scraps, straw shavings, or clay residues. Proper insulation of the roof and foundations, as well as the use of wide walls with a high heat transfer coefficient for partitions, allows for a reduction in heat production, thus lowering the costs of electricity. Another reduction can be seen in the shape of the building. The half-timbered house was erected on a rectangular plan, allowing for cost reduction in both the design and construction stages. The same aspect applies to the simple, gable roof structure. The construction phase itself also mitigated many problematic effects of the chosen technology. Due to the use of clay-straw blocks, which require a period of drying before use and cannot be exposed to moisture, the house was constructed during the warmest months of summer, eliminating the need for energy-consuming heaters.

The concept of reuse is associated with consumer awareness of the reuse of products designated for disposal. One example of this is the decision of a developer to use wooden pallets as interior decor elements in the house, such as a coffee table or garden furniture. Another characteristic feature of the half-timbered house is the absence of rubble and a reduction in the amount of construction waste by utilising materials that are not transported in disposable packaging, such as packaging films, compared to traditional construction technology. A number of ecological technical infrastructure devices were installed on the property. The absence of a sanitary sewer collector necessitated the construction of an environmentally friendly domestic sewage treatment plant. Furthermore, in order to reduce water consumption and save water on the property, two retention tanks were constructed to collect rainwater. The water collected in this way is used for gardening purposes.

The recycling of materials is a fundamental aspect of the economic cycle in the construction sector. During the design and erection of a building, it is crucial to select simple materials with a low carbon footprint that

are relatively straightforward to reintroduce into the cycle, such as wood. The aforementioned example represents an exemplary case of architectural recycling. It was constructed from natural building materials with minimal processing, which facilitates eventual dismantling and enables the majority of materials to be reused for construction or other purposes. The pursuit of recovering and reusing the majority of building materials from previous projects is a crucial aspect of ecological construction (Bukowski & Fabrycka, 2019). The construction of any building is inherently associated with environmental degradation, yet the less degradation, the more ecological the endeavour. The analysed building performs exceptionally well in this regard, thanks to the use of natural and biodegradable materials. Moreover, the construction site was equipped with an appropriate compost bin for the storage of natural waste, thus ensuring the maintenance of cleanliness.

Our heritage encompasses the natural environment, and its future appearance depends on the actions of present and future generations (Assmann, 2018; Bihari, 2023). Society faces numerous environmental challenges, including climate change, waste management, and soil, water, and air pollution (Koop & van Leeuwen, 2017; Yang et al., 2023). To overcome these difficulties and address the increasingly growing shortages of housing resources, pro-environmental and health-promoting principles and sustainable development practices are being introduced. The field of construction has a profound and far-reaching impact on the natural environment (Kietliński, 2015). Consequently, it is imperative to integrate architecture with environmentally conscious solutions (Vaverková et al., 2023).

The changes in living conditions in the 20th century highlight the necessity of considering the environment, with particular emphasis on the rapid decline of fauna and flora (Kietliński, 2015). In the contemporary era, we have more opportunities and access to environmentally friendly technological solutions, which facilitate the implementation of eco-friendly solutions in the construction industry (Zhang & Tu, 2021; Owen, Murtagh & Simpson, 2023). The foundation of this approach lies in the prioritisation of eco-friendly solutions that utilise natural materials which have been minimally processed or recycled (Chang, Long, Zhou & Ma, 2020; Zhang & Tu, 2021). The introduction of earth construction technologies represents a significant step towards sustainable construction (Hall, 2020; Morel et al., 2021). This is a response to the need to reduce the negative impact of human activity on the natural environment. Moreover, in the context of dynamic technological advancement, the availability and advancement of new solutions enable the even more effective and efficient use of earth as a building material.

The technology of building houses with earth is an environmentally friendly solution (Hall, 2020; Islam, Elahi, Shahriar & Mumtaz, 2020; Morel et al., 2021). The method utilises natural materials, typically local ones. Earth is a highly versatile building material. According to the International Centre for the Research and Application of Earth Construction (CRAterre), there are many possibilities for using soil in construction. Shaped earth, earthbags, or earth coverings are just a few examples of soil application in construction. One example of a building constructed using shaped earth is the buildings in Cameroon (Wati, Bidoung, Damfeu & Meukam, 2020; Ganou Koungang et al., 2023; Fig. 6).

The technology of shaped earth involves the direct shaping of moist, pliable soil, typically using hands or traditional, non-mechanised tools. Buildings constructed from rammed earth are shaped similarly to pottery. Shaped earth technology allows for the creation of intriguing architectural forms that do not require additional supporting structures. Controlling shrinkage caused by drying is a key issue, as it is in most other technologies of building with pliable earth. It is notable that shaped earth technology is still employed in numerous countries across Africa (Narloch, 2017).

The utilisation of earthbag technology is a common practice in Oman (Bizzarri et al., 2020). One example of such a building is a residential house constructed with earth-filled bags covered with clay plaster in Shuwaymiyah, Dhofar Governorate, Oman (Fig. 7).

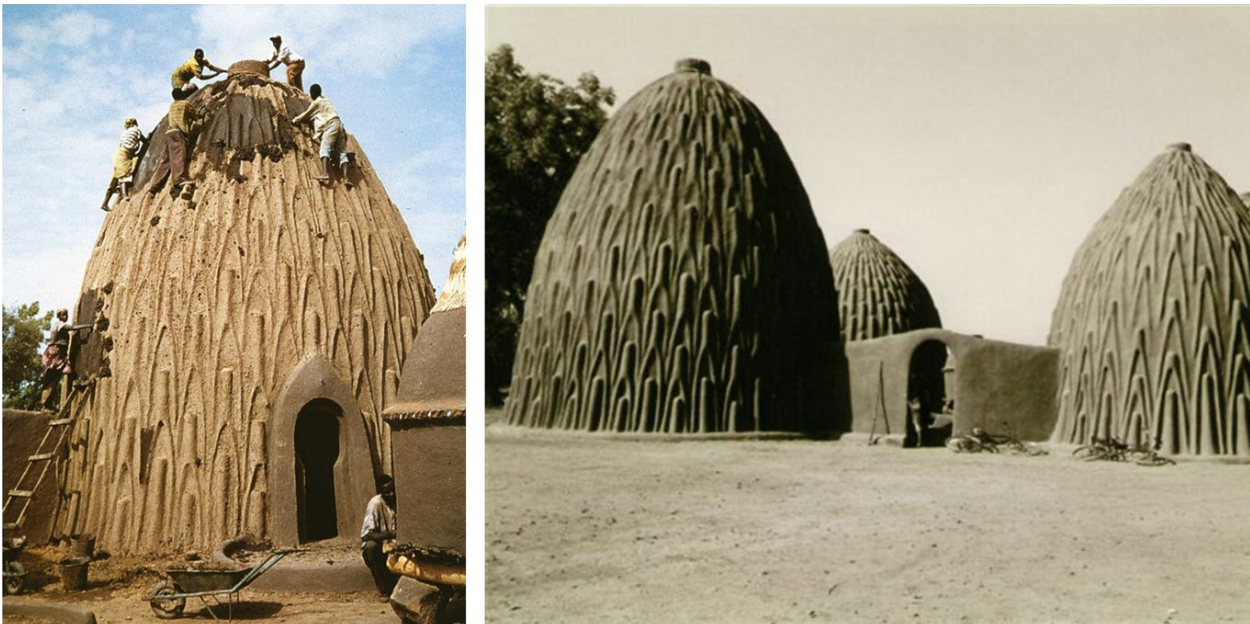


Fig. 6. Shaped earth buildings, Cameroon

Source: Chin (2010).



Fig. 7. House made of bags filled with earth and finished with clay plaster, Oman

Source: SSH (2024).

According to Narloch, this technology involves the filling of building elements with soil made from other materials. One type of this technology is the method of soil-filled bags. Plastic bags serve as a type of disposable formwork. Filled bags are stacked without mortar, and the structure is load-bearing due to the interaction of the core with the soil and the bag's shell (Narloch, 2017).

Figure 8 shows a residential building with a green roof in the Polish shopping centre, Galeria Sfera. The roof is covered with a layer of soil and vegetation, creating a lush and green landscape atop the building. This eco-friendly roofing solution not only enhances the aesthetic appeal of the home, but also provides numerous environmental benefits, including improved insulation, reduction of the urban heat island effect, and mitigation of stormwater runoff. The image illustrates how sustainable building practices, such as green roofs, can be integrated into residential architecture to promote biodiversity, energy efficiency, and overall environmental sustainability (Berg, Adamcová, Barroso, Šourková & Vaverková, 2020; Berg, Hurajová, Černý & Winkler, 2022).

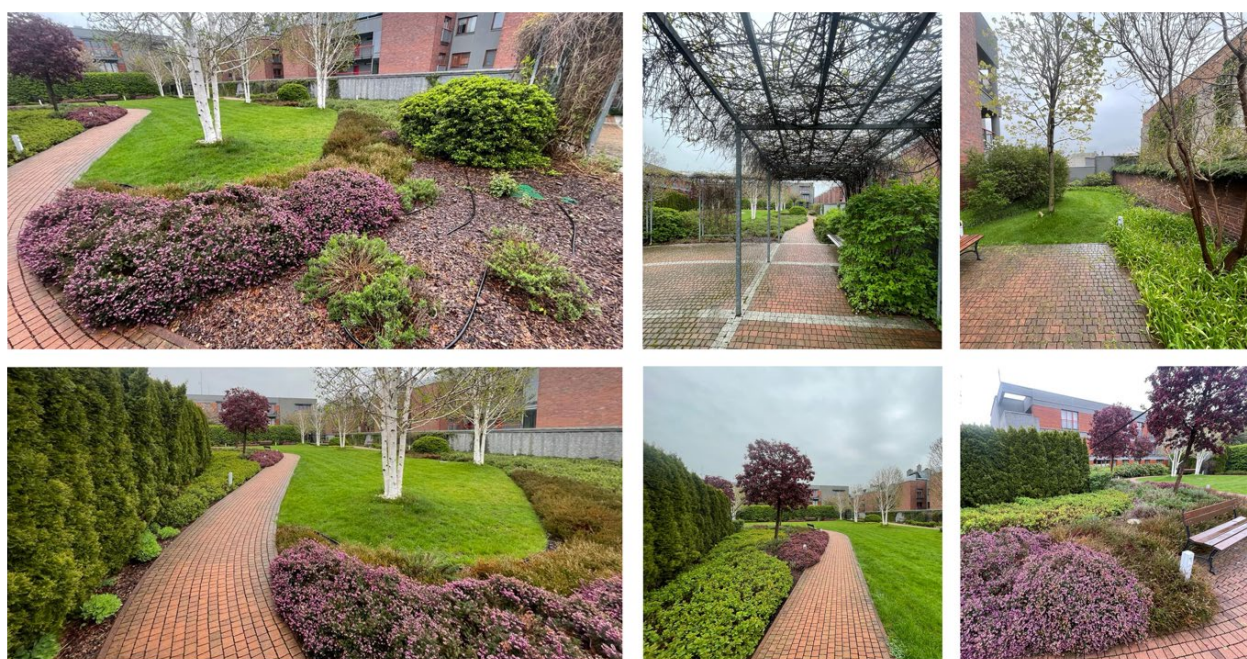


Fig. 8. Residential house with a green roof covered with earth and vegetation, Galeria Sfera, Poland

Source: photos by Magdalena D. Vaverková 2023.

The technique of earth sheltering, also known as green roofing, involves the covering of external building walls, primarily roofs, with a layer of soil. It is a type of green roof where soil is used for insulation and roof covering, reducing the environmental impact of the building and improving energy efficiency. Additionally, it can serve as a way to utilise rooftop space for plant cultivation or gardening. As a result, buildings can be more integrated with nature and more energy-efficient.

Wood is the second most popular natural material, as observed by Sotayo et al. (2020) and Vaverková et al. (2023). In industry literature, it has been noted that green construction is becoming an increasingly common solution for developers, especially in the construction of single-family homes. Wooden houses are particularly popular due to the natural characteristics of wood as a building material. However, it is essential to select appropriate materials and technologies to ensure that the house meets the criteria of sustainable

construction (Bielenis & Swalski, 2021). In order to enhance the durability, reduce the susceptibility to cracking during drying, and enhance the resistance to insects and fungi, it is recommended that wood be harvested during the winter season and during the waning phase of the Moon (Kownacki & Błaszczyński, 2019).

The construction of pagodas (ancient temples in Japan) was historically dependent upon the use of wood obtained during the waning phase of the moon. If properly prepared, wood has the capacity to withstand thousands of years, as it has endured numerous earthquakes and challenging conditions (Kownacki & Błaszczyński, 2019). Currently, moon wood is also being utilised (Fig. 9).



Fig. 9. Hōryū-ji Temple, Japan^a and Hotel Mayr, Italy^b

Source: ^aphotos by Magdalena D. Vaverková by 2023; ^bThoma Holz100 Canada (2024a, 2024b).

Passive houses (Fig. 10) are highly energy-efficient in operation, eliminating the need for a typical heating system (Schnieders et al., 2020; Mushtaha et al., 2021). Instead, they utilise minimal energy for heating, primarily through solar energy and heat generated by occupants and electrical appliances. In instances where supplementary heating is necessary, these structures rely on renewable energy sources such as heat pumps or biomass, which may only be required on days with exceptionally low temperatures. Due to their excellent thermal insulation, these houses consume a minimal amount of heating energy, typically around $15 \text{ kWh} \cdot \text{m}^{-2} \cdot \text{year}^{-1}$, which is comparable to the energy consumption of a small amount of gas, wood, or coal (Kaliszak, 2019).

Wooden skyscrapers are tall buildings constructed primarily from Wood (Almusaed & Almssad, 2022; Niiler, 2022). They are designed to ensure adequate strength and stability of the structure using advanced wood technologies, including glued laminated timber, engineered wood, and cross-laminated timber – CLT (Stach, 2020; Tulonen, Karjalainen & Ilgin, 2020). Figure 11 depicts a wooden skyscraper in Norway.

The buildings discussed in this paper demonstrate that the synergy between construction, sustainable development, and environmental stewardship is achievable (Scharlemann et al., 2020; Vaverková et al., 2023).



Fig. 10. Passive wooden house by Juri Troy Architects, Austria

Source: Quah (2013).



Fig. 11. Mjøstårnet wooden skyscraper, Norway

Source: Polskie Domy Drewniane SA (2020).

While sustainable building practices offer promising solutions for mitigating environmental impacts, it is critical to critically assess the challenges and limitations associated with their implementation. A key challenge is the availability and cost-effectiveness of green materials and technologies (Mariotti et al., 2020; Samadi et al., 2020; Alqahtani, Abotaleb & ElMenshawry, 2021). For example, while wood is a renewable resource, its extraction and processing can still have an environmental impact if not managed sustainably (Akpan, Wetzel & Friedrich, 2021; Schubert, Panzarasa & Burgert, 2022). In addition, the transportation of materials to construction sites can result in carbon emissions, especially if they are sourced from distant locations (Vaverková et al., 2023). The adoption of building technologies utilising earth can also face regulatory and cultural barriers, as building codes and practices often favour conventional materials and methods. In addition, while passive houses and timber skyscrapers offer energy-efficient alternatives, their initial cost and potential long-term maintenance requirements may deter widespread adoption, particularly in regions where traditional construction methods are entrenched (Hasper et al., 2020; Yang, Cho, Yun, Hong & Kim, 2021; Welch, Obonyo & Memari, 2023). In addition, the scalability of these practices to meet the growing demand for housing, especially in urban areas, remains a challenge. Overcoming these barriers will require a collaborative effort among policymakers, industry stakeholders, and communities to incentivise sustainable building practices, invest in research and development, and revise existing regulations to support the transition to greener building practices. By recognising and addressing these challenges, the building sector can move closer to realising its potential as a driver of positive environmental change.

CONCLUSIONS

In the contemporary era, construction professionals must integrate building technology with an awareness of the need to maintain harmony with nature. It is essential that basic human needs are met in a conscious manner, and that modern construction does not disrupt natural processes or the surrounding environment. Environmental practices encompass not only the innovative transformation of wind, sunlight, or geothermal sources into electrical or thermal energy, but also a return to traditional building technologies. The use of natural building materials or proper building orientation are just two examples of classical building solutions that allow for the creation of a healthy and friendly microclimate for humans. The framework of modern construction is established by specific characteristics of eco-friendly buildings. The 6E concept and the 3R principle serve as the foundation for designing sustainable development practices. Whenever possible, natural and recycled materials should be used. By adapting an old structure to a new one, material consumption can be reduced, resulting in a decreased financial investment required for building construction. Modularity, variability, and flexibility of functions, as well as the possibility of frequent adaptation to the environment, should be characteristic features of intelligent buildings. Such solutions will undoubtedly support nature and its resources. By implementing sustainable development practices, people will strike a balance between consumerism and economic and ecological optimisation.

In response to a series of doubts regarding ecological construction, specific principles have been developed to describe this scope of knowledge. Given the current environmental situation and the continuous demand for construction, there is a need for pro-environmental actions at the individual, social, and institutional levels. The most significant characteristics of ecological construction are the 6E concept: economic, energy-efficient, ecological, elastic, aesthetic, and ergonomic, in addition to the 3R principle of reduce, reuse, and recycle. The buildings described in the article met the criteria of 3R and 6E. In the context of ecological construction, this encompasses not only contemporary solutions and technologies but also a return to traditional construction methods. The examples of wooden buildings and timber-framed houses serve to substantiate this thesis and demonstrate that it is possible to combine modernity, ecology, and tradition in construction.

Authors' contributions

Conceptualisation: A.C. and M.D.V.; methodology: A.C.; validation: K.K. and M.K.; formal analysis: A.C.; K.K. and M.K.; investigation: A.CZ.; data curation: A.C.; K.K. and M.K.; writing – original draft preparation: A.C.; K.K. and M.K.; writing – review and editing: M.D.V.; visualisation: A.C.; K.K. and M.K.; supervision: M.D.V.

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

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BUDOWNICTWO PRZYJAZNE ŚRODOWISKU WRAZ Z PRZYKŁADAMI ZREALIZOWANYCH ROZWIĄZAŃ

STRESZCZENIE

W obliczu obecnych wyzwań środowiskowych, przed którymi stoi ludzkość, konieczne jest podjęcie działań proekologicznych, korzystnych dla zdrowia oraz praktyk zrównoważonego rozwoju. Istotne jest globalne wdrażanie ochrony środowiska, mając na uwadze niepokojącą przyszłość oraz długofalowe konsekwencje dla kolejnych pokoleń. Zielone rozwiązania budowlane są wdrażane na całym świecie, ale nie zawsze w odpowiedni sposób. Każda zielona architektura powinna integrować zrównoważony

rozwój i ochronę środowiska przyrodniczego, niezależnie od lokalizacji. Niniejszy artykuł podsumowuje i charakteryzuje koncepcję ekologicznego budownictwa 6E (ekonomicznego, energooszczędnego, ekologicznego, elastycznego, estetycznego, ergonomicznego) oraz zasadę 3R (redukcja, ponowne wykorzystanie i recykling). W artykule przedstawiono również analizę dwóch ekologicznych budynków w Polsce. Pierwszym z nich jest drewniany budynek zlokalizowany we wsi Podgać, który stanowi przykład połączenia nowoczesnego designu i dbałości o minimalizowanie negatywnego wpływu na środowisko przyrodnicze. Został on zbudowany w zgodzie z naturą i wkomponowano go w naturalne środowisko lasu. Dom we wsi Jarzębia Łąka to drugi przykład łączenia tradycyjnego budownictwa, nowoczesnych rozwiązań technicznych z ochroną środowiska przyrodniczego. Przedstawione przykłady inwestycji zostały przeanalizowane pod kątem zasad budownictwa ekologicznego, a następnie porównane z koncepcją 6E i zasadą 3R. W artykule przedstawiono kompleksowe badanie dwóch różnych ekologicznych konstrukcji budowlanych. Badanie to obejmuje charakterystykę techniczną, zgodność z koncepcją 6E, porównanie efektywności ekologicznej oraz wnioski z zaleceniami. Dom Baby Jagi we wsi Podgać jest przykładem harmonijnego połączenia prostoty, funkcjonalności i oszczędności z wykorzystaniem drewna z izolacją w celu przystosowania budynku do całorocznego użytkowania. W obiekcie zastosowano technologie odnawialnych źródeł energii i system zbierania wody deszczowej, co przyczynia się do zrównoważonego rozwoju ekologicznego. Tymczasem do budowy obiektu z muru pruskiego w Jarzębiej Łące wykorzystano cegłę z gliny i słomę, co zwiększyło korzyści ekonomiczne i środowiskowe, które uzyskano także dzięki zastosowaniu w projekcie paroprzepuszczalnych ścian i wydajnej izolacji. Obie konstrukcje stanowią przykład ergonomicznego projektu, ekologicznych praktyk budowlanych i estetycznej integracji z naturalnym otoczeniem. Analiza studium przykładów unaocznia znaczenie włączania rozwiązań przyjaznych dla środowiska przyrodniczego do nowoczesnej architektury w celu stawienia czoła współczesnym wyzwaniom środowiskowym i promowania zrównoważonego rozwoju.

Słowa kluczowe: budownictwo przyjazne środowisku, praktyki zrównoważonego rozwoju, zielone rozwiązania budowlane, koncepcja 6E, zasada 3R

COMMON GOOD IN THE URBAN CONTEXT – INSIGHTS FROM THEORETICAL FRAMEWORKS

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ABSTRACT

The objective of the study is to analyse the role of the concept of *common good* in the contemporary field of urban studies. Through an interdisciplinary literature review, the basic explanation of the concept or *common good* is presented with a focus on *common good* in the urban environment. This work examines how *urban commons* became significant in scientific and public debates, translatable into tangible projects. The research results prove the academic and policy discussions focus on *urban commons* both in theoretical and engaged implementation of experiments in local urban governance. The notion of *common good* in the urban context, applied in territorial governance practices as *commons*, has an expanded international geographical reach, popularised within theoretical and more empirical approaches. The findings reveal a correlation between the discourse on *urban commons* and the proliferation of thematic debates and models; grassroots projects, demonstrating varied impacts by local social, cultural and policy contexts. In conclusion to the study of consecutive contemporary theories, the need to provide accurate elaboration on an *urban commoning* framework can be stated. This is a gap to bridge for enabling practical sustainable applications.

Keywords: *urban commons*, *common good*, *territorial commons*, spatial justice, *commoning*, theoretical framework

INTRODUCTION

General concepts

Urban commons, encompassing specific collectively shared resources (e.g., community gardens and other recreational, often re-adapted spaces), are essential to the social and environmental framework of city life. Over the last century, the perception and function of these *common goods* have undergone significant transformations. Once considered utilitarian elements of urban space landscape, included in everyday planning practices, these spaces are recognised as crucial for enhancing urban liveability and sustainability. This shift, driven by an increasing appreciation for community engagement and environmental sustainability, highlights how *urban commons* are integral to fostering social interactions, providing ecological benefits, and enhancing the overall quality of life in densely populated areas.

In the context of the urban (r)evolution, influenced by historical changes such as industrialisation, urban migration and economic transformations have redefined cities' organisation and governance. The significant

increase in urbanisation during the 19th and 20th centuries made the management of common spaces crucial. In the post-industrial era, challenges like urban growth and environmental degradation prompted cities worldwide to repurpose industrial sites and integrate green spaces. However, the rise of neoliberal policies (Rodotà, 2011) towards the end of the century led to increased privatisation (Dellenbaugh-Losse, Zimmermann & de Vries, 2020) and reduced public expenditures, often resulting in the neglect and decreased accessibility of public spaces and semi-public ones, as well as reduced accessibility to other public goods (Dembinski & Huot, Eds, 2017). *Commons* (being also a subject of interest for lawyers and activists of property rights) and *urban commons* are concepts of intersectional appliance.

The relevance of the study is derived from the need to provide a complex and exhaustive framework for 21st century planning. Today, the interdisciplinary approach to the study of *urban commons* is more relevant than ever as cities confront issues like climate change, social inequality, and spatial exclusion. There is the recognised need for adaptive re-use of spaces (European Commission [EC], 2020). The theoretical frameworks developed in response to these challenges provide a historical perspective, guiding contemporary efforts for future urban planning development (Lennon, 2022) by indicating possible directions to pave (Stavrides, 2016). This literature review traces these developments, examining the evolution of thought and the dynamic adaptations of *urban commons* theories in response to new urban realities (Czornik, 2020).

Aim of the review

The aim of this literature review is to explain the theoretical frameworks that have shaped our understanding of *common goods* in urban contexts, by examining pivotal inputs from the 20th and 21st centuries. The contributors to this thematic pool of knowledge represent very diverse environments – from philosophers (Maritain, 1966), sociologists (Mika, 2017), representatives of the legal community, economists (Polko, Czornik & Ochojski, 2021) and geographers (Heffner et al., 2022) to civil engineers, designers and other specialists (Moroni, 2024). By presenting the reviewed works first chronologically and then thematically, this study highlights the progression and interconnectivity of concepts, synthesising key contributions to the field of *urban commons* studies.

Methodology

In this study, the qualitative literature review methodology was employed, suitable for an in-depth analysis of complex theoretical constructs and their evolution over time. The literature has been selected based on its significance to the field, focusing on key works by leading scholars and seminal publications having shaped *urban commons* theories. The literature is organised chronologically to link subsequent historical developments and shifts in thinking from the 20th to the 21st century, followed by a thematic grouping of notions, providing deeper insights, and connecting various approaches. As the presented thematic field is undergoing current development, the indicated milestones help in orientation within different currents of thought within the field of *urban commons* studies.

Structure of the review

The review is divided into parts. The “Introduction” presents the research approach, aim, and method. The “Theoretical framework and state of the art” section (“Theoretical framework – types of ownership” subsection introduces the explanatory lexical basis, while the “State of the art – theatre of *the commons*” subsection explores early theories and contributions) refers to outcomes of studies in the 20th century. The “Contemporary development on the concept of *common good*” section focuses on recent advancements and shifts (with subsections on the frameworks’ specificities, rules and principles) in the first quarter of the 21st century. The last part in “Results” contains precisions (regarding the positioning of *commons* in regard to other ownership regimes as well as study fields) and research outcomes (“*Urban common*

good – a question of citizens’ rights” subsection lexically reframes expressions present in the literature) to envelop *commons* in their complexity of meanings (with subsections on challenges and a toolbox to reframe the research and empirical *apparatus*). This divided approach not only chronicles the historical progression of ideas but also introduces the material to elucidate themes and patterns, offering a comprehensive, engaging overview of the panorama of *urban commons* studies. The closing reflection, “Critiques and threats to *urban commons*”, summarises the impact of the engaged debate on *commons*. “Discussion” paves the way towards indicating the possible next research steps and further actions. The “Conclusions” section reframes the provided results, being a classifying section for the enumerated approaches, to link with other current contributions to the field and enable further future studies.

THEORETICAL FRAMEWORK AND STATE OF THE ART

Theoretical framework – types of ownership

In the division of goods according to the type of ownership, private goods are distinguished on the scale of limiting the availability and use of the resource (usually the most restricted), then club goods (also known as group goods, the use of which is conditioned by belonging to a community that has the right to use the given resource, i.e. the so-called club), *common goods* (also called *common pool resources* – CPR), and finally public goods (which do not allow for restriction of access), not competitive in their nature (of the access to the resource, such as *commons*) (Koszevska, 2020).

Types of goods classified by ownership and access limitations

Table 1 shows the general classification of goods (Cornu, Orsi & Rotchfeld, 2017) according to their availability: competitiveness and exclusivity for users.

Table 1. Typology of goods based on the criterion of excludability and rivalry

Accessibility criteria		Rivalry	
		yes	no
Excludability	yes	private goods	<i>common goods</i>
	no	club goods (group)	public goods

Note: After the CPRI notion is introduced later in this document, the division of goods by ownership is actualised and precisely described in a detailed manner in Tables 2 and 3.

Source: Koszevska (2020) based on Cornu et al. (2017, p. 75).

Table 1 shows that *common goods* are classified as non-excludable and non-rival by their accessibility features.

Use of urban commons

The urban planning professionals and citizens involved in participatory planning practices, as well as agents contributing to the elaboration and evaluation of public spatial policies, have acknowledged the existence of emerging modes of exercising collective urban action for several decades. Researchers focused on social practices, legal and institutional regulations, and their dynamics approach *commoning* as a stated, already-mature field of examination (Bollier, 2014, 2016). Table 2 illustrates the characteristics of urban territorial goods by their access.

Table 2. Explanatory typology of goods based on the criterion of excludability and rivalry

Low excludability	urban public goods urban landscape, streets, parks, street infrastructure (street lighting, urban monitoring, free mapping services (<i>open access</i> , or provided by municipalities), etc.)	urban common-pool resources courtyards, parking spaces, community gardens, etc.
	urban common goods commonly governed terrains and goods (ex. shared gardens, working spaces, etc.)	
High excludability	urban club goods (group) gated communities, non-public sport areas tennis courts (exclusive group ownership and management)	urban private goods private houses, private apartments, office buildings
Criterion	low rivalry	high rivalry

Note: *Urban common goods*, understood typically as commonly governed terrains and goods (ex. shared gardens, working spaces, etc.), would be classified in the intersection of “low excludability” and “low rivalry” sectors, (exceptionally in “high rivalry”).

Source: own elaboration based on Polko et al. (2021, p. 16) and Ostrom, Gardner and Walker (1994, p. 7).

Table 2 shows that *common goods* are classified as non-excludable and non-rival by their accessibility features. It describes if citizens are easily excludable from the access to them, meaning also that users may experience a range of rivalry to access the good.

Importance and utility for urban planning actors

Precision in explaining the meaning of *common good* in the urban context is valuable for designers, policymakers (and activists), policy analysts and researchers in urban planning and geography (Eisenschitz, 2022). Elements considered as *common good* in the urban space may translate into specific ways of managing the city space and its design. This is the work of architects, planners, and other industry designers in the field of spatial management. Spatial planning is often in the hands of local government employees, as planning and urban work often require cooperation in teams. For this reason, it may be useful to review the paradigm of exercising power and activities in the field of urban space management. In local authorities’ governance, numerous decisions are made, requiring answers to fundamental questions. In situations of conflicting actions (democratisation, dialogue, participation...), determining their consistency with the spirit of the *common good* might improve such actions’ contribution to the improvement of urban planning processes. Reflection on this concept equips actors of collective action with a lens focused on the cohesion of collective territorial governance actions, including in the rural dimension. It may seem that elaborate theories in human science are distant from lessons from praxis, though these two intertwine in many approaches.

State of art – theatre of commons

The international transdisciplinary scene of scientific and scholarly debate represents different currents and tendencies in observing and evaluating the dynamics of *commons* (as resources) and *commoning* (as activities). *Tragedy* and *comedy* (and the *tragicomedy*) reveal the *commons* characteristics in theme literature. Thus, it can be referenced as a dialogue, separated into acts.

“Tragedy of the Commons” (Hardin, 1968)

In reference to the growing global urban community, pessimism on resources has become an integral element of the reasoning, though the referential works on *commons* in the 20th century (Hardin, 1968) were based on a descriptive qualitative study of natural resources viewed as *commons*. The radiating theoretical exploration of *commons* can be assigned to Garrett Hardin’s 1968 essay, “The Tragedy of the Commons” (Hardin, 1968), where he argued that individual self-interest in unregulated *commons* leads to resource

depletion. The situation of over-exploitation led to the elaboration of the process, i.e., *the tragedy of the commons*, through the practical access to the use of a non-restrained community of users. The dysregulated access to the resource (e.g., pasture) implicated the functioning of *free riders*, tempted to exploit the natural resource by privatising the profits derived from them. The reflection touches on the concept of overuse. Hardin's solution was either government intervention or private ownership as a means to manage resources sustainably. His pessimistic approach may be linked to the energy crisis of his epoch, and the – little examined and commented – zoological foundations of his research workshop, leading to generalised assumptions about human behaviour at the social scale (Koszevska, 2020).

In the 21st century, this situation has gained a new label in planning, used for the urban environment: “Not in my backyard” – NIMBY – referring to people's lack of communal reference (Domaradzka, 2018).

“Comedy of the Commons” (Rose, 1986)

Later, Hardin's observation was countered by the opposing statement, which led to work on “Comedy of the Commons” (Rose, 1986). She examines infrastructural resources such as roads and waterways, where the maintenance cost is publicly shared (recreational spaces such as the beach ball playgrounds, following the principle of recreational use: “the more, the merrier”, and the commerce that offers social benefits). The law scientist wrote a reflection on public property use and the users' convictions: “When things are left open to the public, they are thought to be wasted by overuse or underuse. No one wishes to invest in something that may be taken from him tomorrow, and no one knows whom to approach to make exchanges. (...) All resort to snatching up what is available for ‘capture’ today, leaving behind a wasteland. From this perspective, ‘public property’ is an oxymoron: things left open to the public are not property at all, but rather its antithesis. (...) The Romans, whose legal thinking greatly influenced later European law, were sufficiently interested in ‘public property’ to separate it into at least four categories”. In reference to the Northern American understanding on the benefits and challenges of private property, Rose wrote: “some kinds of property should not be held exclusively in private hands, but should be open to the public or at least subject to what Roman law called the ‘jus publicum’: the ‘public right’ (...), service to commerce was a central factor in defining as ‘public’ such properties as roads and waterways. Used in commerce, some property had qualities akin to infinite ‘returns to scale’. Thus here, the commons was not tragic, but comedic, in the classical sense of a story with a happy outcome.” This may “suggest that commerce might be thought a ‘comedy of the commons’ not only because it may infinitely expand our wealth, but also, at least in part, because it has been thought to enhance the sociability of the members of an otherwise atomised society” (Rose, 1986, p. 728). Ending the discourse on commons' comedy, the author wrote: “I conclude by suggesting that in the twentieth century there may be other versions of the comedy of the commons, and other practices that share with commerce the power to enhance our sociability. We might even think that properties devoted to such non-commercial uses as recreation or speech could achieve their highest value when they are accessible to the public at large” (Rose, 1986, p. 728).

“Tragicomedy of the Commons” (Daniels, 2014)

To describe intermediating features of *commons*, the term *tragicomedy* – a post-modernist label of classics – is also being employed: “One strand is plagued with challenges, most of which can be traced back to the internal characteristics of the commons – the nature of the resource, the traits of its users, the way the commons is governed, and the value placed on the commons resource. The second strand is one of hope – that through governance we can overcome these internal challenges and this inertia” (Daniels, 2014). The author overarched the two opposing narratives of *commons*: the pessimistic tragedy of Garret Hardin, and the optimistic comedy by Carol Rose. The joint presentation resulted in the term ‘tragicomedy’, which represents the binding tension between the opposing scenarios. In the conclusion the author weights the two presented approaches: “However, hope in this context is fragile. It depends on not only guarding against the push toward tragedy but

also assuring that the way we govern the commons changes to both consider surprises and shifts in the way we value the commons. Fortunately, (...) the end of each commons story is ours to write”.

To summarise this part, interestingly, the diversity of authors and opposing trends in the interpretation of values of *commons* is not dominating the hope of these authors and actors of collective action to elaborate commonly (jointly, collectively) a new way of cooperating, responding to changing needs of society and their territorial reign. As an alternative to popular existing models of governance, communing is also called the third way (Bollier, 2014; Hudson, Rosenbloom & Cole, Eds, 2019).

Contemporary developments of the concept of common good

Hardin’s perspective was defeated by Elinor Ostrom, who, in her seminal work: “Governing the Commons” (1990), provided empirical study cases of communities successfully managing common resources through collective action and self-governance (CPRs).

Functionally described use – Ostrom’s institutional framework (1990)

Although the trans-locality of these actions is apparent, their copy-paste adaptability is limited (to the size of the operation – Ostrom, local conditions and traditions). This approach is described in a further part of the article, describing contemporary development on *commons*. Elinor Ostrom has established a long-standing common pool resources examination (Ostrom et al., 1994; Ostrom 2008, 2013), being translated into diverse languages and integrated within different disciplines. The approach has been developed and continued by followers. Her contribution was granted a Nobel Prize in 2009 for its analysis of economic aspects of governance, especially by communities, which widely popularised her research.

Design principles for sustainability of commoning

The eight design principles (Ostrom, 1990) for managing commons are defined as follows (described subsequently): (1) The group boundaries and spatial resource limits must be clearly defined (This condition refers to the implemented exclusion of non-entitled and non-involved parties). (2) The rules of governing and appropriating the *common good resource* (limiting the time, place, and number of involved participants of the CPR) and the rules of contributing to the resource (through the input of time, work, materials, financial allocations) by participating entities must be aligned with the local environment needs and local conditions of its governance structure. (3) The possibility of modifying collectively the binding rules by all the parties affected by their functioning (regarding the use, management, and contribution to the maintenance of the resource) needs to be precisely defined. (4) It is necessary to monitor the use of the *common good* by internal means or the responsibility should be transferred to external socially trusted actors (It is also required for the external governors and authorities to respect the elaboration and outcomes of internal regulations established within the CPR. The monitoring from outside reinforces the common structure). (5) The cross passing of established rules of functioning must be possible to effectively punish with sanctions to exclude violating behaviours. (6) The conflict resolution mechanisms should be effective and accessible to apply. (7) Community self-organisation and recognition of this management by higher-level administration (e.g., through state regulations). (8) For larger common resources: organisation of use in the form of enterprises for the common good of resources being nested tiers of a larger interconnected multi-level system.

Complementary rules to Ostrom’s work – commons in the city (Foster & Iaione, 2015)

To develop and precisely define the framework of Elinor Ostrom (1990), five key design rules were defined for the *urban commons* by Sheila R. Foster and Christian Iaione (Hudson et al., 2019): (1) collective (multistakeholder) governance, (2) enabling state representatives (i.e. local authorities in cities), (3) social and economic pooling (presence of autonomous participatory institutions), (4) experimentalism (in adaptive

iterative place-based design), (5) technological justice (co-ownership of infrastructure and data). According to the authors, elaboration of the five enumerated principles serves the emergence, development, and sustainability of *urban commons*, enabling the local community to co-create in ways adapted to 21st century dynamics (and power games).

RESULTS

Challenges of studying a diverse property regime's features

Conducting research on the categories of management and ownership requires constant updating of knowledge, followed by the capturing of records within contemporary phenomena; the traditional criterion of property ownership should be supplemented with the aspect related to the actual management of a given property (as shown in Table 3). It is not only private (which can entail the multitude of entities under the brand of a legal person, such as a joint venture or a corporate company) and public ownership that are the main typology elements, but a growing diversity of shared ownership and management in different frameworks is also expanding (Cornu et al., 2017). A simplified array of types of ownership and management (establishment of rules & change elaboration, responsibility for access control) is presented further.

Table 3. Typology of goods based on the criterion of ownership and management

Category	Private ownership	State ownership	Common ownership	“Free access”
Entity keeping the title to the ownership	private entity joint ventures holdings housing communities	State political and administrative entities of central, regional, and local (local actors)	Common Pool Resource Institutions (CPRI) members (ex. trade unions, guilds of professional chambers, cooperatives, associations, co-inheritance)	nobody
Exclusion of non-owning entities	yes	no (optionally: foreigners and entities exempted from taxation)	yes (non-members of the club)	no
Entities responsible for access control	entities holding the right to ownership (guaranteed by the state)	State	CPRI members	nobody
Entities participating in the management process (taking decisions)	entities holding the right to ownership	political and administrative entities (actors)	CPRI members	nobody

Source: Koszevska (2020) based on Cornu et al. (2017, p. 76).

Table 3 shows the general division of goods based on the ownership criterion using the *common pool resources institution* (CPRI) category, i.e., organisations and institutions established for managing common property. It distinguishes individual, and typical contemporary forms of organisation management, such as companies, housing communities, etc., and four basic types of ownership of goods: private, state, common, and “free access” (ownership – indefinite or unlimited).

Additional criteria considered are the organisational form of ownership, actors responsible for access control (exclusive control for the possessors or exclusive control not only for the possessors – owners – but the possibility of excluding an also-given good from general use: controlled access) and actors participating in the decision-making and management process.

Table 3 presents the typology of goods based on the criterion of ownership and management. The common ownership via CPRI excludes from ownership entities not belonging to the club. Entities partake in CPRI functioning through the membership access control.

Building on Ostrom's framework, recent scholarship has expanded the understanding of *commons* to include not only environmental resources but also social, cultural, and digital *commons*. Scholars have explored the way *commons* encompass a broad range of resources, including knowledge, culture, and urban spaces. The focus has shifted towards understanding *urban commons* as complex socio-spatial phenomena (Foster, 2011) that embody environmental, economic, and social dimensions (Foster & Iaione, 2015, 2019).

The *commons* movement has expanded specifically around chosen current problems of space ownership in Italy – particularly around buildings in Rome (Rodotà, 2011) and natural resources in Naples (Vittoria, Ragozino & Esposito De Vita, 2023), in France within human sciences examinations, such as philosophy (Dardot & Laval 2015) and economics (Festa, 2016) and in Greece (Stavrides, 2016) and other countries (ex. USA, UK, Belgium...).

Since Elinor Ostrom's work (Ostrom, 1990), the debate on *commons* and *commoning* (Stavrides, 2016) has been present in disciplines such as economics and law (Rodotà, 2011), philosophy, and sociology (Dardot & Laval, 2015). Though it is necessary to refer to the complex heritage of science in this area (Piechowiak, 2012; Hudson et al., 2019). The reflection on the community regulations dates from the ancient times of mankind (Coriat, Ed., 2015). Even in in-depth monographs devoted to the notion of *common good*, there is an apparent difficulty in clearly defining the subject (Dardot & Laval, 2015). This background motivated the author of this research to mobilise the cognitive apparatus to undertake this cross-disciplinary analysis, explaining the phenomenon of established and emerging *commoning* practices, which influence existing territorial planning procedures by their actions, changing the local landscape. In some cases, the propagating tendency of temporary territorial *commoning* occupations reaches is permanent impact, shaping local spatial planning laws (Czornik, 2020).

Urban common good – a question of citizens' rights

In the urban studies framework, the notion of justice is connected to the “just city” idea (Fainstein, 2010), where planners explore how common spaces beyond public or private status regulate inequalities of contemporary societies. Even though the question of justice has been of interest within political philosophy and science for several centuries, behavioural researchers were cautious with regulatory definitions. However, critical left-wing-oriented scholars developed this in the late 1960s through 1970s. The western literature accommodated moral questions within the description of social phenomena, but justice in the urban realm remained undefined (Fainstein, 2014). The influential work of Lefebvre contributed to the field by attributing to the space the characteristics of social construction, to which everybody should have a right (Lefebvre, 1967). By the end of the 20th century, the spatial dimension of justice mobilised researchers to be more descriptive, in the context of the neo-liberalised experience of shaping the city. The communicative rationality and spatial justice approaches focused on democracy and equity, process and outcome of the expression and place of diversified participants of urbanised areas. The governance principles: democracy, diversity, and equity, are also contradictory, according to Fainstein. The author stated that structural changes were harder to imply than rhetoric of urban justice. Urban policies are prone to be adapted to residents' need to improve their quality of life by introducing to the public discourse the criteria of the “just city” concept while focusing less on competitiveness (a key factor at the municipal level of strategic planning and policy elaboration).

In urban studies, common spaces beyond public or private status regulate inequalities of contemporary societies and how societal challenges and movements (Kubicki, 2020) can be expressed within this part of public life, which is apparent in public spaces in the city (Harvey, 2012, 2013).

There is the conceptual link between the right to the city (Lefebvre, 1967), considering that negative effects of urbanisation should be opposed by the ‘Right to the city’ movement, lobbying for new

methods of urban management; the concept of fighting in the name of the revendication of access to the city space (Lefebvre, 1967; Harvey, 1968, 2012).

As *common* spaces are meant to be, but do not always appear to be explicitly just spaces, it is challenging to reconnect ethical tensions of commonalities and justice. Despite the conceptual link between spatial justice and *commoning*, it needs to be clarified in a comprehensive theoretical framework to avoid the misunderstandings. This concept used in the fight for the just city generates scepticism on the rules within the community of commoners' practices of commoning, the process' permeability to the newly involved and the disadvantaged. The relations of power within common forms of governance, economic resources sustaining such processes, and the dynamics between *communities of commoners* and public institutions deserve to be observed to verify the regulations of these dynamics.

Within the contemporary discussion as presented in the previous chapter, we can observe the rising paradigm of *urban commons* as a way to express the community's collective action and a shift from theoretical concepts of *commons* towards practical applications in diverse intersectional contexts. This shows that *urban commons* are an applied field of study, which is closely following and deeply rooted in the developments of a changing world. Although the contemporary debate on regulations of *commons* started in the 20th century, it was in the 21st century that the accumulated research brought precisions on their efficiency and sustainability.

Many works on the *common good* postulate the need to conduct further research on these issues to assist procedures in the city space for balancing the *spatial justice*, in a place where a large and diverse community lives.

Classification of thematic and disciplinary approaches in *commons* studies

Table 4 illustrates the interdisciplinarity of studies on the idea of *common good* and the diversity of study approaches and orientations, suitable for each discipline and its subject of examination with an adjusted methodology. It provides a schematised disciplinary classification and interpretation of methodological examinations and an attributed focus on the study aims.

Table 4. Interdisciplinarity of studies on the idea of *common good*, grouped by field frameworks

Field of science	Approach to the study of <i>commons & common good</i>	Scientific discipline
Humanities	ethical cultural	philosophy, cultural and religious studies
Theological sciences	ontological transcendental	theological sciences
Social sciences	social – materialistic	sociological sciences social economic geography social communication sciences
	economic – managerial	economics and finance political and administrative sciences
	institutional – economic	management sciences law spatial management
	materialistic – ecological	environmental engineering civil engineering
Engineering and technical sciences	economic – institutional (design-oriented)	architecture and urban planning, civil engineering

Note: the authors' classification is based on the Polish qualification of scientific disciplines (Rozporządzenie Ministra Nauki i Szkolnictwa Wyższego z dnia 20 września 2018 r. w sprawie dziedzin nauki i dyscyplin naukowych oraz dyscyplin artystycznych. Dz.U. 2018 poz. 1818), the latest based on the international classification of the Organisation for Economic Co-operation and Development (OECD).

Source: Koszewska (2020).

As seen in the synthesised critical choice and interpretation of the general trends and methodologies (Table 4), these approaches complete themselves by the description of different aspects of the *commons* thematic field. The described research procedures (e.g., economy) are suitable to disciplinary positioning and diversified approaches of the applied methodologies. In the thematic literature, we can observe both the highly theoretical angle of study (e.g., philosophy, theology, law), in parallel to others, elaborated on the choice of local territorial *commoning* case studies (economy, geography, sociology, ethnology, urban planning and architecture...), (Mika, 2017; Koszevska, 2020).

DISCUSSION

Critiques and threats to *urban commons*

While *urban commons* are praised for their potential to foster community engagement and democratise public space, they also face significant challenges. Although the described hereby classical dispute between tragedy (Hardin, 1968) and comedy (Rose, 1986), commented as tragicomedy (Daniels, 2014) and completed by the comprehensive use proposal (Ostrom, 1990) defines the opportunities and dangers of *commoning* as a way of governing the resource, new observations arise, suitable to new local collective experiences and problems (often in response to spatial conflicts). The side effects include secondary exclusivity (hidden, not-officially expressed preferences of limiting the access to the use of the resource), privatisation, and unexpected commercialisation of the *commoning* spaces (such as externalities – ex. pollution).

Weaknesses. Although spatial justice and *commoning* are semantically related, this needs to be further clarified in a comprehensive theoretical framework to avoid misinterpretations. The critical question to be asked is: who profits directly from the *commoning* activity and who contributes to its resource?

As demonstrated, the study of the *commons* leads to a proposal of a way of functioning differently from the typical division into public and private property. Thus, the chances of elaborating and testing new models of collective action seem promisingly inexhaustible. The facilitated international cooperation in the globalised era of new digital *commons* and results of open access scholarly works facilitate the exchange of thoughts, local and disciplinary perspectives, research results, and testing experiences. The presence of international programmes and documents encourages cross-pollination of practices, both in empirical experimentation and theoretical frameworks testing.

Urban common good concept potential

At the end of the presented discourse, it is essential to evaluate the opportunities of *commoning* as a practice included in spatial, and particularly, urban planning procedures. Planning processes and *commoning* seem to guide this field into innovative participatory actions, though the balance between idealised communal participation and the pragmatic realities of managing common resources in urban settings is worth discussing.

Strengths. *Commoning* has, amongst other characteristics, the strong capacity of demonstrating pedagogies of the societal drive towards equality and justice in the cityscape. This agency can engage its actors, users or target groups of people invited to take part in the *urban commoning* activity, touching upon participation and inclusion.

CONCLUSIONS

The presented literature research addresses gaps in the body of scholarly material in the domain of architecture and territorial planning, in particular, in the urban realm. The mentions of the *common good* concept, particularly in the technical literature, tend to flatten the richness of possible interpretations and trans-disciplinary complexity of study into *commons*. On the other hand, emerging authors tend not to exhaust

the topic of *urban commons*, linked to methodological deficiencies, which are still evolving and being developed across the globe (Koszewska, 2020).

The concept of the quest for spatial justice applies to the urban *commoning* activity in a direct way. It deserves theoretical and practical reflection and explanations through in-depth analysis to support the *commoning* movement.

Toolbox for reading the theories and conceptualising commons practicalities

The article contributes to the establishment of actualised knowledge construction, enables academic and civic discussion by providing (by the author's own elaboration and quotation) the basic disciplinary vocabulary. The author's presentation makes it possible to join the ongoing international debate on the new efficient modes and models of possible joint and just social territorial action and intervention with the goal of establishing a sustainable environment. This review proves the evoked diversity of disciplinary approaches, intertwined in applied *commoning* practices. By establishing foundations for further works, it is paving the way for following in-depth profiled theoretical and empirical case studies on the detailed classification of just roles of *commons* actors.

Within the summarised research, the author has examined and presented the existing theories and methods to establish the framework, enabling further theoretical, but also empirical interdisciplinary studies, with an emphasis towards civil engineering (architecture, urban planning, sustainability in the built environment). The methodology used was profiled to achieve a broad understanding of the complex phenomenon of common ownership, governance, and use.

This study of theories illustrates the transformative power of urban commons, reinforcing civic democratic dialogue in action for elaborating models and urban policies in mixed dynamics of social representatives with local authorities.

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DOBRO WSPÓLNE W KONTEKŚCIE MIEJSKIM – PRZEGLĄD POJĘĆ I TEORII

STRESZCZENIE

Celem prezentowanego studium jest analiza koncepcji dobra wspólnego we współczesnej urbanistyce. W interdyscyplinarnym przeglądzie literatury przedmiotu przedstawiono podstawy badań na temat pojęcia dobra wspólnego ze szczególnym uwzględnieniem miejskiego dobra wspólnego. W ślad za rosnącym zainteresowaniem badaniami nad miejskimi dobrami wspólnymi podążają eksperymentalne praktyki w lokalnym planowaniu i zarządzaniu przestrzennym. Wyniki badań świadczą o rosnącym zainteresowaniu akademickim i w publicznej dyskusji o polityce przestrzennej. Niniejsza praca przedstawia przełożenie teoretycznej koncepcji miejskich dóbr wspólnych z debaty naukowej na możliwość wdrażania projektów społecznych w zurbanizowanym środowisku. Podsumowując, pojęcie dobra wspólnego w kontekście miejskim, stosowane w zarządzaniu terytorialnym jako *urban commons*, ma międzynarodowy zasięg geograficzny, dzięki popularyzowaniu w ramach badań naukowych nad jego zastosowaniem. Wyniki ujawniają relację między dyskursem na temat miejskich dóbr wspólnych a rozprzestrzenianiem się modeli projektów, zróżnicowanych pod względem lokalnych uwarunkowań kulturowych i politycznych.

Słowa kluczowe: miejskie dobra wspólne, dobro wspólne, terytorialne dobro wspólne, sprawiedliwość przestrzenna, procesy uwspólniania, podstawy teoretyczne

DETERMINING THE COORDINATES OF UNMANNED AERIAL VEHICLES

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ABSTRACT

The purpose of the work was to develop a method for determining unmanned aerial vehicles' (UAVs) coordinates, trajectory and parameters of their spatial movements by means of kinematic projection. The paper analyses the use of technologies for determining coordinates and spatial movements of aircraft trajectories. The principle of the kinematic scheme of fixing moving objects by means of orthogonal and kinematic design has been developed. The principle scheme of determining UAV coordinates by kinematic projection was studied. The theoretical mathematical dependencies of the determination and calculations of the coordinates of spatial movements of unmanned aerial vehicles have been practically verified. The main object of research in this work was the theory of kinematic design as a means of graphically displaying the patterns of spatial movements of objects. The subject of the study was the specific features of searching and recording the trajectories of spatial movements of unmanned aerial vehicles in order to determine the coordinates of their instantaneous location in space. In the process of conducting theoretical and experimental research, methods and techniques of physical and mathematical modelling of fast-moving processes and mathematical statistics of analysis and classification of their results were used. The basis of the experimental study was the theory of mapping coordinates and trajectories of spatial movements of moving objects by means of graphic geometry when combining classical orthogonal design with dynamic features of kinematic design. For an objective assessment of the results of the theoretical and experimental study of the dynamics of objects moving in space, the classical theory of research planning with a mathematical apparatus for processing their results was used. Graphical models of UAV coordinate fixation were made with the use of computer technology and the AutoCAD graphic editor software.

Keywords: unmanned aerial vehicles, military sphere, kinematic scheme, electromagnetic radio waves

INTRODUCTION

In recent decades, unmanned aerial vehicles (UAVs) have been widely used in both the industrial and military sectors. Manoeuvrable, efficient in terms of energy consumption, relatively cheap in production and operating conditions, and easily remotely controlled by modern means of radar navigation, these flying machines are already widely used and have a very real prospect of even wider application.

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The range of fields of application of flying machines and the variety of their sizes and purposes are due, first of all, to the capabilities of radar digital communication, which ensures reliable control of the flights of these machines over considerable distances. The task of detecting the coordinates and trajectories of enemy reconnaissance or subversive unmanned aerial vehicles should be perceived as a separate and particularly important problem in military affairs.

Modern means of anti-aircraft defence are capable of neutralising any enemy aircraft that collects intelligence information both at low and high altitudes without any particular problems. However, for this, they need accurate (plus or minus a dozen metres) coordinates of the spatial location of the enemy flying object. However, it is extremely difficult to obtain such accurate information in the case of UAVs, including drones, using modern radar communication methods (Kutsenko, 2017; Chernyshev & Kutsenko, 2018).

That is why the task of creating a theory of kinematic mapping (Kalynovska, Hlohovskyy & Pulkevych, 1994; Pulkevych, 1994) arose before descriptive geometry as a science of geometric mapping of the interposition of space elements. “Kinematic projection” should be understood as a projection in which all its elements, namely the centre of projection, focal figures of projecting complexes and congruences, the object of projection (so-called proto-image) and the carrier of projections (so-called picture plane) can make mutually independent spatial movements in space and time.

The purpose of the research is to develop a method for determining UAVs’ coordinates, trajectory and parameters of their spatial movements by means of kinematic projection.

The main tasks of the study include:

- analysis of the technologies used for determining coordinates and trajectories of spatial movements of aircraft,
- development of a basic kinematic scheme for fixing moving objects by means of orthogonal and kinematic design,
- study of the principle scheme for determining UAV coordinates by kinematic projection,
- practical verification of the theoretical mathematical dependencies of the definition and calculations of coordinates of spatial movements of unmanned aerial vehicles.

MATERIAL AND METHODS

The main object of research in this work was the theory of kinematic design as a means of graphically displaying the patterns of spatial movements of objects.

The subject of the research was the specific features of searching for and recording the trajectories of spatial movements of unmanned aerial vehicles in order to determine the coordinates of their instantaneous location in space. In the process of conducting theoretical and experimental research, methods and techniques of physical and mathematical modelling of fast-moving processes and mathematical statistics of analysis and classification of their results were used. The basis of the experimental study was the theory of mapping coordinates and trajectories of spatial movements of moving objects by means of graphic geometry when combining classical orthogonal design with dynamic features of kinematic design. For an objective assessment of the results of the theoretical and experimental study of the dynamics of objects moving in space, the classical theory of research planning with a mathematical apparatus for processing their results was used. Graphical models of UAV coordinate fixation were made with the use of computing equipment and the AutoCAD graphic editor software.

REVIEW OF PRIMARY LITERARY SOURCES

The problem of finding and determining the coordinates of aircraft is quite actively dealt with by military specialists and scientists. Thus, a certain version of the solution to this problem is reflected in the work by Chernyshev and Kutsenko (2018). To improve the method of determining the coordinates of unmanned aerial

vehicles in the area of anti-terrorist operation (ATO), the authors evaluated the accuracy of determining the coordinates of UAVs using the so-called difference-range method in a mobile passive radar system based on short-range anti-aircraft systems. The results of their research showed that the errors of the determined aircraft coordinates by this method are insignificant, and in some cases, the location of the UAV is generally commensurate with the size of the searched objects (Kalynovska, Hlohovskyy & Pulkevych, 1994; Pulkevych, 1994; Kutsenko, 2017; Chernyshev & Kutsenko, 2018). The mathematical dependencies obtained by the authors make it possible to choose the optimal ones from the point of view of ensuring minimal errors in the location of combat vehicles with passive direction finding equipment.

Certain disadvantages of this differential-range-measuring method are its unsuitability for UAVs flying along predetermined trajectories of movement without accompanying radio frequency control of their spatial movement. The absence of electromagnetic impulses to control the flight of such UAVs makes them “invisible” to direction finders and also makes it impossible to detect their coordinates.

An equally significant drawback of this method of determining UAV coordinates is the need for a significant amount of technical means for its implementation, in particular, four manoeuvrable radio direction finders and a command post located 500–3,000 m from each other. Between 10 and 15 people will be needed to service this equipment.

RESULTS AND DISCUSSION

The essence of the proposed method is illustrated in the figures. Figure 1 shows the layout of radar location stations (RLS) RLS N1 and RLS N2 on the Earth’s surface, which are distant from each other by $a = 500\text{--}1,000$ m. Here, the point $C \equiv CL$ shows the conditional location of the command post (CP), which is a certain distance from both radar location stations. Three points, A , B and C , define the basic reference plane, which is denoted by $\alpha(A, B, C)$.

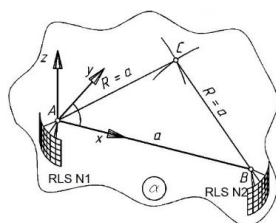
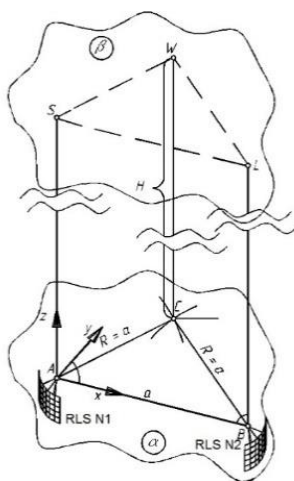


Fig. 1. Base plane α reference with the Cartesian coordinate system

Source: own work.

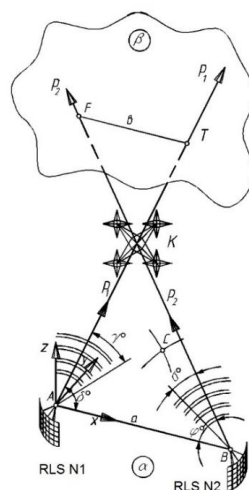
In one of the RLSs, for example, at point A , a Cartesian three-dimensional spatial coordinate system with mutually perpendicular axes X , Y and Z is introduced. The X axis of this coordinate system originates at point A and is directed at point B , which symbolises the location and coordinates of the second RLS device. The Z axis originates at point A , perpendicular to the X axis, and is directed upwards. The Y axis also begins at point A and is perpendicular to the X and Z axes. The X and Y axes, like two mutually perpendicular straight lines, form the so-called base plane α . It is in this base plane that the intermediate point C is located, equidistant at a distance a from both RLSs.

Having set the height H , which is 1.2–1.5 times greater than the approximate flight altitude of the UAV, points S , W and L are set on perpendiculars to the base plane at points A , B and C . As illustrated in Figure 2, These three points S , W and L are set in space picture plane $\beta(S, W, L)$, which is parallel to the base plane $\alpha(A, B, C)$ and removed from it at distance H , that is, $H = AS = CW = BL$; $\alpha(ABC) \parallel \beta(SWL)$.



Source: own work.

When turned on, both RLSs direct electromagnetic radio waves in the expected direction of the location of the UAV (Fig. 3). On the RLS monitors, the direction of the projecting rays passing from each of the RLSs through the spatial location point of the UAV, and their angles of inclination to base plane α , i.e., $\gamma = p_1 \wedge \alpha$ and $\sigma = p_2 \wedge \alpha$, are recorded. In addition, for a full-fledged coordinate binding of the projecting beams to the introduced coordinate system, for each of the projecting beams p_1 and p_2 , the angle of its inclination to line a connecting both RLSs is also determined. That is, $\delta = p_1 \wedge AB$ and $\phi = p_2 \wedge AB$ (Fig. 3).



Source: own work.

According to the coordinates of the RLS location points and the angles of inclination γ , σ , δ and φ of the projecting beams to base plane α and line α connecting both RLSs, the computer of the command post displays both projecting beams p_1 and p_2 .

The point of intersection of the projecting beam with the picture plane is sought either by analytical or graphical methods. In the analytical method of searching for the intersection point, the analytical equation of the projecting ray is specified as the equation of a straight line passing through a known point (A or B) with given coordinates at a known angle of inclination to base plane α , and the analytical equation of picture plane β passes through three points S , W and L with known coordinates. The point of intersection of the straight line with the plane in this case will be the desired point, the coordinates of which simultaneously satisfy both the equation of the straight line and the equation of the plane.

When applying the graphical method, the coordinates of the point of intersection of the projecting beam (p_1 or p_2) with picture plane n are searched for by the method of finding the point of intersection of the straight line with the plane.

Thus, in the introduced Cartesian coordinate system with the beginning of its axes at point A , which symbolises the location of one of the RLSs, it is possible to unambiguously indicate the location of the desired UAV. This can be done either by having significant calculations of the lengths of the segments $t_1 = AK$ and $t_2 = BK$ located on the projecting beams p_1 and p_2 , and known from the RLS monitors of the angles of inclination to the base plane $\delta = \omega(p_1 \cap p_2) \wedge \alpha(ABC)$ of the plane ω formed by the projecting beams. And also by the known angles of inclination δ and γ of the projecting beams p_1 and p_2 to the line connecting both RLSs.

Another possible option for determining the location of the UAV in the airspace is calculating its coordinates XK , UK and ZK using the proposed mathematical dependencies.

The instantaneous locations of the UAV, i.e. points with step-by-step calculated coordinates, displayed on the operator's screen in three dimensions, will display the spatial trajectory of the flying object's movement. And the recorded time intervals between the recording of the momentary locations of the UAV and the movements completed during these time intervals will provide information about the speed of movement of this object.

Consider an example of implementation of the proposed method. For simplicity, let the radar stations RLS N1 and RLS N2, as well as point C , be located at the same geographic height. Then, the base plane defined by these three points A , B and C will be an imaginary horizontal plane. Let the distance a between the radar stations be $a = |AB| = 500$ m, and the predicted flight height of the sought UAV is within 800–950 m.

Let us imagine projecting two projecting beams p_1 and p_2 onto the sought UAV, each of which starts at its point of installation of the radar station. That is, let $RLS\ N1 \equiv A_{\in p_1}$ and $RLS\ N2 \equiv B_{\in p_2}$.

Let us take different values of the angles of inclination of the projecting rays to the line a connecting the radar stations. That is, let $\delta = |p_1 \wedge AB| = 70^\circ$ and $\phi = |p_2 \wedge AB| = 80^\circ$. Let us set the distance of the sought UAV from the radar stations through the angle of inclination ν formed by the projecting rays p_1 and p_2 to the base plane $\omega(p_1 \cap p_2)$, $\alpha(A, B, C)$, i.e., $\nu = \omega \wedge \alpha$. Let $\nu = 60^\circ$. In the example we considered, angle $\delta = 70^\circ$, $\phi = 80^\circ$ and $\nu = 60^\circ$ are set, and in real situations, the numerical values of these angles will be set and fixed on the monitors of radar stations according to the directions of the vectors of the radio waves generated by them, which will pass through the wanted UAV. That is, relatively speaking, in this case, it does not matter whether the wanted UAV is distant from the radar, for example, by 1 km, 1.5 km or 2 km. Instead, it is important that the projecting beam clearly indicates the direction of the locations of this UAV, and the available technical means fix the above-mentioned angles of its inclination to the AB line and the base plane α .

Let us set a picture plane located in the air space at a height of, for example, $H_1 = 1,000$ m, $H_2 = 1,250$ m, $H_3 = 1,500$ m.

The task is to calculate the coordinates of the wanted UAV in the three-dimensional Cartesian coordinate system arranged at the initial point $A = RLS\ N1$.

The calculated mathematical dependencies, initial data and calculation results are given in Table 1. The final results of the calculations are the coordinates of the wanted UAV displayed in the table. Thus, for the first option considered, with a conditionally specified angle $\nu = 60^\circ$ of the inclination of the plane

$\omega(p_1 \cap p_2)$ formed by the projecting rays p_1 and p_2 to the base plane $\alpha(\Delta ABC)$, the calculated coordinates of the location of the UAV were $K(X_K; Y_K; Z_K) = K(337; 463; 802)$ m. That is, its flight height is $Z_K = 802$ m, and it is $t_1 = 985$ m distant from the first radar station RLS N1 and $t_2 = 940$ m from RLS N2.

In the second variant, when changing the angle to $\nu = 70^\circ$, coordinate $X_K = 337$ m remained unchanged, coordinate $Y_K = 317$ m, and the flight height (Z coordinate) increased to 870 m. A similar pattern is observed when the angle ν is further increased to 80° – coordinate X_K is unchanged, coordinate $Y_K = 162$ m decreases, and the flight height, displayed by coordinate $Z_K = 912$ m, increases. This shows that the obtained mathematical dependencies respond sensitively to changes in initial conditions and are amenable to logical interpretation.

Table 1. Calculated dependencies for determining UAV coordinates

Calculation parameters		Dependencies of parameter calculation	Value of the parameters at angle ν° of the inclination of the plane of projecting ray $\omega(p_1 \cap p_2)$ to base plane $\alpha(\Delta ABC)$		
Parameter name mathematical	Marking				
Tilt angles					
– planes of projecting rays to the base plane	ν	$\nu^\circ = \omega(p_1 \cap p_2) \wedge \alpha(\Delta ABC)$	60°	70°	80°
– of the first projecting beam p_1 to the line between the radars	δ°	$\delta^\circ = p_1 \wedge a$	70°	70°	70°
– of the second projecting beam p_2 to the line between the radars	ϕ°	$\phi^\circ = p_2 \wedge a$	80°	80°	80°
– angle between two projecting rays	γ°	$\gamma^\circ = p_1 \wedge \alpha$	30°	30°	30°
– distance between radar N1 and radar N2	a	set	500 m	500 m	500 m
Distance to the picture plane	H	set	1,000 m	1,250 m	1,500 m
Distance between the basic α and picture plane β along plane $\omega(p_1 \cap p_2)$ of the projecting rays	L	$L = \frac{H}{\sin \nu_0}$	1,155 m	1,330 m	1,523 m
Distance from the UAV to line a between radar N1 and radar N2	h	$h = L \left(1 - \frac{b}{a + b} \right)$	926 m	926 m	926 m
Distance from the UAV to radar N1	t_1	$t_1 = h_1 \sqrt{1 + (\text{ctg} \delta)^2}$	985	985	985
Distance from the UAV to radar N2	t_2	$t_2 = h_1 \sqrt{1 + (\text{ctg} \phi)^2}$	940	940	940
Distance between the projections of projecting rays on picture plane β	b	$b = \frac{L \cdot \sin \gamma}{\sin \delta \cdot \sin \phi} - a$	124 m	218 m	322 m
UAV coordinates					
X	X_K	$X_K = t_1 \cdot \cos \delta$	337	337	337
Y	Y_K	$Y_K = h_1 \cdot \cos \nu$	463	317	162
Z	Z_K	$Z_K = h_1 \cdot \sin \nu$	802	870	912

Since the mathematical dependencies, as follows from the examples given, are quite simple and are derived from stereometry and analytical geometry, the calculation programs created for the calculations will not be complicated. However, they must be compatible with the radar software.

CONCLUSIONS

1. The types of RLS search for moving objects that were created at the time were determined to be insufficiently effective for determining the coordinates, velocities and trajectories of the spatial movement of unmanned aerial vehicles flying mainly at high altitudes. The main reason for this layering on the return signal reflected from the sought moving object is other extraneous signals reflected from the Earth's terrain, tall trees, hills, buildings, etc.
2. The method of determining the position of the UAV in the airspace by means of kinematic design, which is based on the calculation of the distance of the aircraft from the RLS stations in the Cartesian coordinate system, is not sensitive to extraneous false signals reflected from the Earth's terrain. Due to this, it is more accurate compared to the difference-ranging method and other methods of RLS search for aircraft.
3. In addition to determining the coordinates, velocities and trajectories of UAV spatial movements, the kinematic design method is suitable for determining the location of moving objects on land and water surfaces, as well as in water depths. This gives it prospects for wide application in both military and civilian fields. In particular, in construction and aerial surveying, during automated processing of forest lands and land plots, and when searching for schools of fish in deep waters.

Authors' contributions

Conceptualisation: I.A., I.S.; methodology: I.S., D.B.; validation: I.A., O.S.; formal analysis: I.S., O.S.; investigation: Y.R., D.B.; resources: Y.R., I.K.; data curation: I.A.; writing – original draft preparation: Y.R., V.R.; writing – review and editing: I.S., V.R.; supervision: O.S., I.K.; project administration: O.S., V.R., I.K.

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

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WYZNACZANIE WSPÓŁRZĘDNYCH BEZZAŁOGOWYCH STATKÓW POWIETRZNYCH

STRESZCZENIE

Celem pracy było opracowanie metody wyznaczania współrzędnych, trajektorii i parametrów ruchu przestrzennego bezzałogowych statków powietrznych (BSP) za pomocą projekcji kinematycznej. W artykule dokonano analizy zastosowania technologii wyznaczania współrzędnych i trajektorii ruchów przestrzennych BSP. Opracowano zasadę kinematycznego schematu mocowania poruszających się obiektów za pomocą konstrukcji ortogonalnej i kinematycznej. Badano podstawowy schemat wyznaczania

współrzędnych BSP metodą rzutu kinematycznego. Teoretyczne zależności matematyczne wyznaczania i obliczania współrzędnych ruchów przestrzennych BSP zostały zweryfikowane w praktyce. Głównym przedmiotem badań w tej pracy była teoria projektowania kinematycznego jako środka graficznego przedstawiania wzorców przestrzennych ruchów obiektów. Przedmiotem badań była specyfika wyszukiwania i rejestracji trajektorii ruchów przestrzennych BSP w celu wyznaczenia współrzędnych ich chwilowego położenia w przestrzeni. W procesie prowadzenia badań teoretycznych i eksperymentalnych wykorzystano metody oraz techniki modelowania fizycznego i matematycznego procesów szybko przebiegających oraz statystykę matematyczną analizy, a także klasyfikacji ich wyników. Podstawą badań eksperymentalnych była teoria odwzorowywania współrzędnych i trajektorii ruchów przestrzennych poruszających się obiektów za pomocą geometrii graficznej przy połączeniu klasycznego projektowania ortogonalnego z dynamicznymi cechami projektowania kinematycznego. Do obiektywnej oceny wyników teoretycznych i eksperymentalnych badań dynamiki obiektów poruszających się w przestrzeni wykorzystano klasyczną teorię planowania badań z matematycznym aparatem do przetwarzania ich wyników. Graficzne modele fiksacji współrzędnych BSP wykonano przy wykorzystaniu technologii komputerowej oraz oprogramowania edytora graficznego AutoCAD.

Słowa kluczowe: bezzałogowe statki powietrzne, sfera wojskowa, schemat kinematyczny, elektromagnetyczne fale radiowe

A COMPARATIVE ANALYSIS OF LANDFILL PRACTICE BETWEEN POLAND AND INDONESIA

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ABSTRACT

This research addresses the global challenge of waste management (WM) by comparing landfill management practices in Poland (Radiowo landfill) and Indonesia (Kebon Kongok landfill) to define the differences in landfill WM systems and analyse the main challenges in implementing effective landfill management WM systems in Poland and Indonesia. The data was analysed by employing the rapid impact assessment matrix (RIAM). The analysis focused on three critical areas: gas management, leachate management and landfill reclamation. The results showed that the Polish landfill demonstrated high efficacy, particularly in leachate management with water quality impact (96), gas emissions control with methane extraction (96) and site reclamation for site restoration (96). For these purposes, the landfill uses advanced leachate treatment technologies and drainage systems. Conversely, Indonesian landfill practices show severe inefficiencies, with negative scores in almost all sectors. The lowest score was in leachate management with water quality impact (–48), gas emissions with air quality impact (–48) and site reclamation in community space development (–48). The study contributes to the sustainable waste management discourse, providing actionable insights for policymakers and environmental managers.

Keywords: landfill management, RIAM, gas management, leachate management, reclamation

INTRODUCTION

Waste management (WM) and disposal have emerged as critical global economic and environmental issues (Awino & Apitz, 2024). The increasing volume of waste generated in most countries signifies a growing challenge that demands immediate attention. This increasing trend can be attributed to various factors, including population growth, urbanisation, industrialisation and changing consumption patterns – particularly in developing countries (Kumari & Raghubanshi, 2023). Improper WM practices have significant consequences, leading to environmental pollution, soil degradation, water contamination, and air pollution (Ziraba, Haregu & Mberu, 2016; Abubakar et al., 2022; Mor & Ravindra, 2023; Sharma, Kaur & Aditya, 2023). Therefore, effective WM practices are paramount for addressing the environmental challenges of increasing municipal solid waste (MSW) generation levels.

Poland has one of the lowest per capita MSW generation rates in Europe (Koc-Jurczyk, 2023). According to Statistics Poland and the National Waste Plan 2023 of Poland in Ciula, Bajdur, Gronba-Chyla and Kwaśnicki (2023), approximately 39.8–40% of MSW was disposed of in landfills in 2020 and 2021. As Poland's waste management practices are evolving towards sustainability, landfill reclamation emerges as a crucial element of WM because landfills pose significant environmental threats, such as soil and groundwater contamination by heavy metals, self-heating and spontaneous combustion, leading to fires, harmful emissions and the release of particulate matter, microorganisms and toxic compounds (Szulc et al., 2022). One of the landfills in Poland that has successfully implemented landfill reclamation is the Radiowo landfill. In contrast, Indonesia's WM system currently focuses on collecting, transporting and dumping waste in designated final disposal sites (FDS) areas. Unfortunately, many of these FDS rely on open dumping, causing severe environmental problems like soil, water and air pollution (Luthfiani & Atmanti, 2021).

As a developing nation, Indonesia faces challenges in implementing the best WM practices. However, the country has taken a step forward by enacting the 2008 WM Law, which requires all provinces to switch from open dumping to sanitary landfills. Open dumping is defined as a location where solid wastes are thrown away in a way that does not safeguard or protect the area, is susceptible to open burning and is accessible to local vectors and scavengers (Yasin & Usman, 2017). Meanwhile, sanitary landfills involve burying or covering waste to accelerate decomposition and prevent fires and disease (van Wee & Witlox, 2021). Despite these regulations, around 66.81% of landfills in Indonesia still implement open dumping systems because WM is not yet a priority for local governments, coupled with regional management funds still being below 1% of total regional expenditure.

The Indonesian province of Nusa Tenggara Barat (NTB) exemplifies the pressing need for improved WM practices nationwide. Recognising the severity of the issue, NTB passed Regional Regulation No 5 of 2019, which focused explicitly on WM strategies. Data from the Department of Environment and Forestry of NTB reveals a discrepancy between waste generation and proper management. In 2023, NTB produced roughly 3.9 million tonnes of waste. However, only 1.9 million tonnes were processed or disposed of in designated final disposal sites, which signifies a significant amount of waste – approximately 2 million tonnes, needing better management (Khalid & Agreista, 2023). Improper landfill management practices further complicate the issue, posing a severe environmental threat (Winahyu, Hartoyo & dan Syaikat, 2019; Emalya, Munawar, Rinaldi & Yunardi, 2020). A concerning report by Inside Lombok (2022) highlights the environmental consequences of the oldest and biggest landfill in NTB, which is the main object of this study, namely Kebon Kongok. It has experienced multiple problems – from organic pollution caused by gas generated by the municipal solid waste (MSW) to leachate contamination of groundwater. Immediate action is needed to prevent environmental damage and safeguard ecosystems, biodiversity and human health – especially in the face of rising global MSW generation (Abubakar et al., 2022; Awino & Apitz, 2024).

The WM is a comprehensive framework of strategies and procedures designed to identify, control and handle all types of waste. This framework encompasses the entire waste lifecycle, from its initial generation to final disposal, to minimise waste production, prevent improper disposal and ensure safe and responsible handling through collection, transportation, treatment and disposal methods (Mubasalat, 2021). Meanwhile, Bacinschi, Rizescu, Stoian and Necula (2010) identify WM as the process of handling discarded materials and plays a critical role in safeguarding public health and the environment. The complexity of landfills is increasing, and many aspects may affect emissions into the air that are poorly documented today (Rim-Rukeh, 2014). For instance, the EU Directive on waste landfills has introduced specific goals for reducing the volume of disposed waste and stringent requirements for landfilling and landfill sites by encompassing activities like monitoring waste generation, collecting it from its source, transporting it to designated facilities and processing it through recycling or responsible disposal. Effective WM minimises the negative impacts of waste on surrounding areas and promotes resource recovery through recycling (Vaverková, 2019).

There are three crucial factors resulting from the generation of MSW in landfills. The first is the formation of leachate, which contains a high concentration of pollutants that can contaminate bodies of water (Tchobanoglous & Kreith, 2002). According to Vaverkova (2019), leachate is formed through complex physical, chemical and biological interactions between waste products, moisture and external influences. The quality and quantity of leachate are influenced by factors such as waste composition, waste characteristics, landfill age, landfill operational practices and the amount of water that seeps into the landfill, including the volume of rainfall (Vaverková, 2019; Zhao, Liu, Feng, Li & Li, 2021). Second, the formation of gas in landfills (LFG) is a result of numerous field studies conducted worldwide to confirm that LFG has significant contributions to global greenhouse gas emissions (Fourie & Morris, 2004). Landfill gas (LFG), consisting primarily of methane (50–60%) and carbon dioxide (40–50%), is created by waste disposal facilities that receive organic waste as a result of biological, chemical and physical processes occurring in the landfill (Scheutz & Kjeldsen, 2019).

The third important factor is landfill reclamation, which restores and repurposes closed landfill sites for beneficial use, such as parklands or renewable energy installations (Veleva et al., 2017). The process of landfill reclamation is a promising solution to the challenges posed by rapid urbanisation in our society (Liu et al., 2023). Reclaiming land involves various tasks, including shaping the landfill, installing a degassing system, sealing the surface, implementing drainage and adding a layer of soil and vegetation (Koda, Podlasek, Osiński, Markiewicz & Vaverková, 2021). Reclamation is a long-term process that involves protecting waste landfills from harmful environmental effects and integrating them with the surrounding area. It can take more than a decade and must be done following a schedule specified in the consent to close the landfill (Majewski, 2021).

Therefore, driven by the three essential factors of generating MSW to the landfill, this research aims to: (i) define how LGM from MSW differs between Poland and Indonesia and what factors contribute to these differences; (ii) analyse the main challenges in implementing effective leachate management in landfill WM systems in Poland and Indonesia; (iii) determine the difference in the process of reclamation between Poland and Indonesia

MATERIAL AND METHODS

Materials

This study explores landfill management practices in two contrasting locations: the Radiowo landfill in Poland (Fig. 1a) and the Kebon Kongok landfill in Indonesia (Fig. 1b). According to Koda et al. (2022), the Radiowo landfill is the largest in Poland and is located near Warsaw. Radiowo is a sanitary landfill with an embankment style, covering approximately 20 ha and reaching a height of approximately 60 m. It served as the disposal site for Warsaw's MSW from the early 1960s until 1991, receiving all MSW from non-composted and composted materials. The landfill handled around 600 tonnes of waste daily, resulting in approximately 300 tonnes of non-composted waste. Finally, the reclamation project was conducted from 1999 to 2017 (Table 1).

On the other hand, the Kebon Kongok landfill in Indonesia is located in Nusa Tenggara Barat (NTB), West Lombok. Kebon Kongok has been operational since 1993 and covers an area of around 13 ha, with a designated capacity of 991,800 m³. In 2021, the landfill had reached its maximum capacity (Table 1). However, it still receives 300–400 tonnes of waste daily from Mataram City and West Lombok (Khalid & Agreista, 2022). The landfill implements various waste management activities, including waste sorting, supervision, equipment operation, recycling, leachate management, biogas handling, buffer zone creation and even the utilisation of scavengers and black soldier fly larvae (*Hermetia illucens*) for waste processing (Alawiyah, 2016).

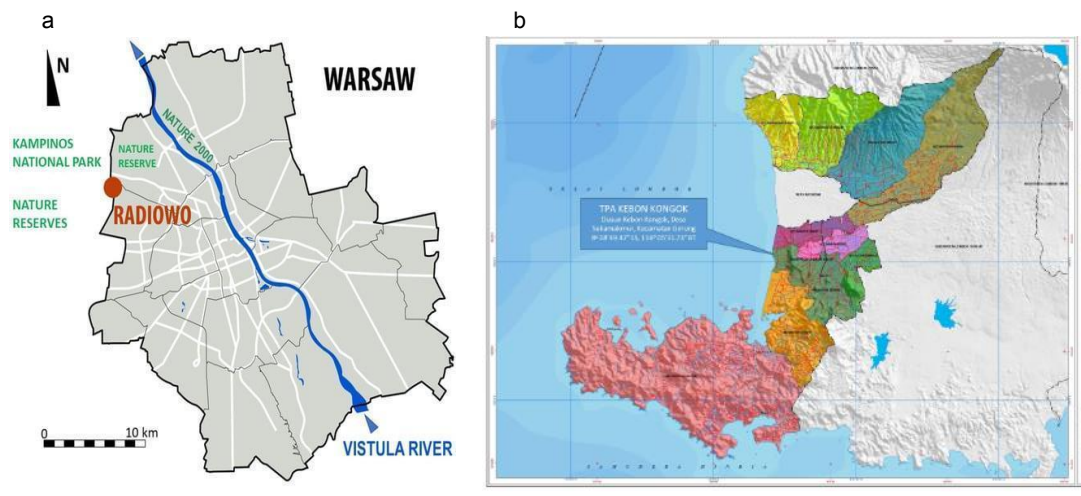


Fig. 1. Location map of Radiowo landfill in Poland (a) and Kebon Kongok landfill in Indonesia (b)

Source: ^aKoda et al. (2022); ^bDepartment of Environment and Forestry of West Nusa Tenggara province (2022).

Table 1. Summarised of important elements from Kebon Kongok landfill and Radiowo landfill

Specification	Kebon Kongok landfill	Radiowo landfill
Landfill type	open dumping	sanitary landfill
Area	13 ha	20 ha
Operation year	1993–present	1999–2017
Type of MSW	– biodegradable and non-biodegradable materials – hazardous household waste like batteries, paints and chemicals	– non-composted materials like plastics, textiles, glass and debris – composted materials
Types of WM activities type	– waste sorting – recycling – leachate management – biogas handling – scavengers and black soldier fly (<i>Hermetia illucens</i>) larvae for waste processing	– leachate management – gas management – reclamation
Climate	dry and rain seasons	four seasons: winter, spring, summer and autumn

Source: own work.

METHODS

This study employs both qualitative and quantitative approaches. The qualitative approach relies primarily on non-numerical data and direct observation (Crang, 2002). The quantitative approach uses the RIAM method to conduct a comprehensive comparison of landfilling practices in two countries. The study employs the RIAM method, specifically the Rapid Impact Assessment Matrix as shown in Figure 2. The RIAM method offers a systematic and structured approach to assessing environmental impacts, taking into consideration the specific contexts of Poland and Indonesia’s landfill management practices. This analysis applies the RIAM method to compare the landfilling practices and their respective impacts in both countries.

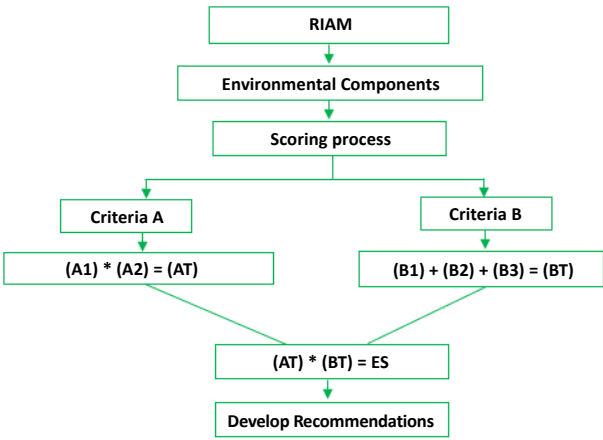


Fig. 2. Flowchart for RIAM matrix work
Source: Resen, Abdul Razzaq and Abbood (2023).

The rapid impact assessment matrix (RIAM) framework systematically classifies environmental components into distinct categories such as leachate, gas emissions and reclamation. Each category is evaluated through specific criteria to ensure a comprehensive assessment. The first criterion, importance (A1), gauges the significance of an issue across local, regional or national scales. Higher importance denotes broader impacts and a greater priority for intervention. The second criterion, magnitude of change/effect (A2), assesses the severity of impacts. This necessitates more substantial interventions for more significant magnitudes. The third criterion, permanence (B1), evaluates whether impacts are temporary or permanent. Permanent impacts require long-term solutions. The fourth criterion, reversibility (B2), considers the ease with which impacts can be reversed. Irreversible impacts are of greater concern. Finally, the fifth criterion, cumulative effect (B3), examines the cumulative nature of impacts. It recognises that cumulative effects can intensify over time and require more strategic planning. Through this detailed and methodical approach, the RIAM framework facilitates informed decision-making and sustainable management of environmental components.

In the context of leachate management, the effectiveness of leachate treatment and its impact on groundwater and surface water quality are of paramount importance. In terms of gas emissions, the extraction and containment of methane, along with the overall impact on air quality, are critical factors to consider. Reclamation efforts focus on the restoration of landfill sites and the development of community spaces, ensuring both environmental recovery and community benefits. This systematic approach ensures that all potential impacts are thoroughly evaluated and addressed, promoting sustainable environmental management. The evaluation of the impacts of each option on environmental components was conducted using the criteria and scales presented in Table 2 (Pastakia & Jensen, 1998).

To utilise the evaluation process, a matrix was created for each option, with components identified and individual criteria scores assigned to each cell. The assessment considered six factors influenced by environmental impact, namely water quality impact, methane extraction, air quality impact, site restoration and community space development. The treatment effectiveness is categorised into three main groups: leachate management, gas emissions and reclamation within the environmental component. During the scoring process, each environmental component received scores for A1, A2, B1, B2 and B3, based on an average of expert opinions regarding the environmental effects of each alternative.

The environmental score (ES) for each component was calculated and then multiplied by the contractual scores detailed in Table 3. The sum of these values was divided by the total number of factors to determine

the overall ES for the comparative analysis of landfill practices between Poland and Indonesia. Consequently, the alternative with the least environmental impact was identified and proposed as the best practice for improving waste management in Indonesia.

Table 2. Assessment criteria in RIAM analysis

Criteria	Scale	Description
A1: importance of condition	4	important to national/international interests
	3	important to regional/national interests
	2	important to areas immediately outside the local condition
	1	important only to the local condition
	0	no importance
A2: magnitude of change/effect	+3	major positive benefit
	+2	significant improvement in status quo
	+1	improvement in status quo
	0	no change/status quo
	–1	negative change in status quo
	–2	significant negative disbenefit or change
	–3	major disbenefit or change
B1: permanence	1	no change/not applicable
	2	temporary
	3	permanent
B2: reversibility	1	no change/not applicable
	2	reversible
	3	irreversible
B3: cumulative	1	no change/not applicable
	2	non-cumulative/single
	3	cumulative/synergistic

Source: own work.

Table 3. The range bands of environmental scores in RIAM analysis

Environmental score	Range band	Contractual score	Extent of the environmental impact
From +72 to +108	+E	5	major positive change/impacts
From +36 to +71	+D	4	significant positive change/impacts
From +19 to +35	+C	3	moderately positive change/impacts
From +10 to +18	+B	2	positive change/impacts
From +1 to +9	+A	1	slightly positive change/impacts
0	N	0	no change/status quo/not applicable
From –1 to –9	–A	–1	slightly negative change/impact
From –10 to –18	–B	–2	negative change/impacts
From –19 to –35	–C	–3	moderately negative change/impacts
From –36 to –71	–D	–4	significant negative change/impacts
From –72 to –108	–E	–5	major negative change/impacts

Source: Valizadeh and Hakimian (2019).

RESULTS AND DISCUSSION

This research uses three environmental component variables to analyse the conditions of landfill practices in Poland and Indonesia. Next, each component is evaluated using certain criteria to determine its impact on the landfill site. The assessment scores use RIAM analysis for environmental components: leachate management, gas emissions and reclamation of landfill practices in Poland and Indonesia.

The condition of environmental components in Poland, based on criteria scores (A1, A2, B1, B2 and B3), has a significant impact on landfill management (Table 4). In Poland, the components of leachate management, in terms of water quality impacts, gas emissions for methane extraction and site relocation reclamation, have significance for national or international interests (A1) with the highest degree (4) on the scale. Meanwhile, in terms of the magnitude of the change (A2), it has a positive benefit with a degree of 3 for all environmental components except for the impact of air quality in controlling gas emissions, which requires improvements to the status quo with a degree (2). Likewise, permanent (B1) and unchangeable (B2) indicators have the same degree (3) for both criteria, apart from being cumulative (B3) with degree (2).

Table 4. Results of the matrix components within the Radiowo landfill site located in Poland

Environmental component	Criteria	A1	A2	B1	B2	B3	Score
Leachate management	treatment effectiveness	3	3	3	3	2	72
	water quality impact	4	3	3	3	2	96
Gas emissions	methane extraction	4	3	3	3	2	96
	air quality impact	4	2	3	3	2	64
Reclamation	site restoration	4	3	3	3	2	96
	community space development	3	3	3	3	2	72

Source: own work.

Overall, the risk assessment scores for Poland's landfill practices show strong performance in every environmental component (Fig. 3). The first component is leachate management, which includes treatment effectiveness and water quality impact. Based on the total criteria scores (A1, A2, B1, B2 and B3), water quality impact has a higher score of 96 compared to treatment effectiveness. Similarly, the gas emissions component is highly effective, with methane extraction scoring 96 compared to air quality impact. These indicate that Poland's landfill has robust methane management practices. The last component is reclamation, which also shows high efficacy, particularly in site restoration with a score of 96, reflecting the success of the restoration initiative.

The environmental impact assessment score of Kebon Kongok landfill in Indonesia shows a negative score on the magnitude of change (A2) for all criteria (Table 5). These consistent negative assessments underscore the severity of the environmental challenges associated with landfill operations. Meanwhile, Indonesia received the highest score on the indicators of permanence (B1) and reversibility (B2), with a score of three among all indicators. Overall, the results of this research underscore the need for immediate and effective environmental management practices to address the significant negative and detrimental impacts of the Kebun Kongok landfill.

The RIAM's analysis scores for Indonesian landfills show different results compared to Poland in managing environmental components (Fig. 4). The results indicate that Indonesia faces significant challenges, particularly in leachate management, where treatment effectiveness and impact on water quality received negative scores of –24 and –48, respectively. Likewise, gas emissions management in Indonesia

has a negative score for both methane extraction and air quality criteria. Meanwhile, in the reclamation component, Indonesia received a positive score of 24 for site restoration but obtained a negative score for community space development.

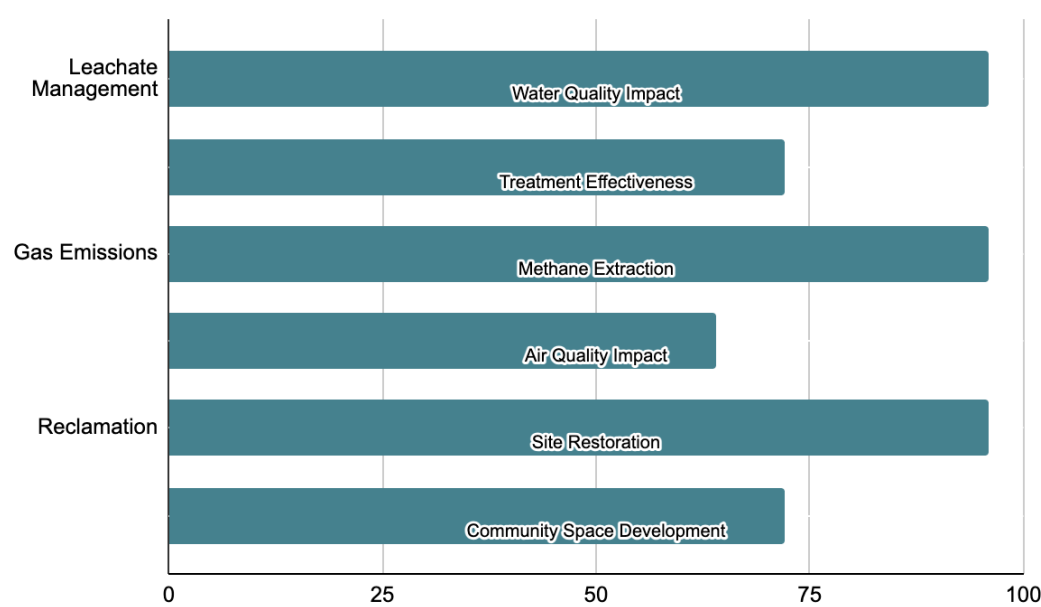


Fig. 3. Poland’s total environmental component score based on criteria

Source: own work.

Table 5. Results of the matrix components within the Kebon Kongok landfill site located in Indonesia

Environmental component	Criteria	A1	A2	B1	B2	B3	Score
Leachate management	treatment effectiveness	3	−1	3	3	2	−24
	water quality impact	2	−3	3	3	2	−48
Gas emissions	methane extraction	2	−2	3	3	2	−32
	air quality impact	2	−3	3	3	2	−48
Reclamation	site restoration	3	1	3	3	2	24
	community space development	3	−2	3	3	2	−48

Source: own work.

The average environmental impact of the Radiowo landfill on leachate management and water quality has a significant positive effect, scoring 5 on the contract scale. It falls within the +E band range, with environmental scores (ES) of 72 and 96, respectively. However, efforts to control gas emissions and improve air quality need to be increased, as indicated by an ES of 64, placing it in the +D category. Additionally, the Radiowo landfill scores 96 and 72 on the ES scale for reclamation efforts at relocation sites and community space development areas, respectively, falling within the E band range (Table 6).

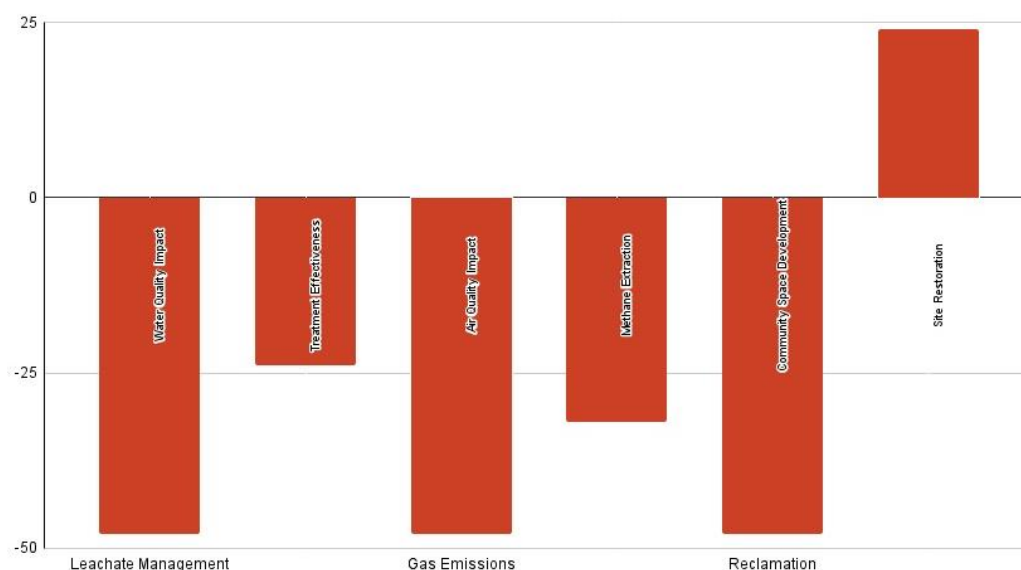


Fig. 4. Total score of Indonesian environmental component score based on criteria

Source: own work.

Table 6. Description of the extent of the environmental impact at the Radiowo landfill in Poland

Environmental component	Criteria	ES	Range bands	Contractual scores	Extent of the environmental impact
Leachate management	treatment effectiveness	72	+E	5	major positive change/impacts
	water quality impact	96	+E	5	major positive change/impacts
Gas emissions	methane extraction	96	+E	5	major positive change/impacts
	air quality impact	64	+D	4	significant positive change/impacts
Reclamation	site restoration	96	+E	5	major positive change/impacts
	community space development	72	+E	5	major positive change/impacts

Source: own work.

In contrast to the Radiowo landfill in Poland, the environmental impact analysis at the Kebon Kongok landfill in Indonesia revealed several concerns regarding various environmental aspects. In terms of leachate management, treatment effectiveness shows a significant negative impact with an ES score of -24 (-C band range), indicating a serious negative impact on water quality. Similarly, the indicators for gas emissions and methane extraction, as well as air quality, fall into the -C and -D categories respectively. In the reclamation component, site restoration is the only area that shows positive results, indicating a moderate positive impact with a score of 24 (+C), signifying success in site restoration. However, community space development received a significantly negative rating, with a score of -48 (-D), highlighting major weaknesses in creating useful community spaces (Table 7).

Table 7. Description of the extent of the environmental impact at the Kebon Kongok landfill in Indonesia

Environmental component	Criteria	ES	Range bands	Contractual scores	Extent of the environmental impact
Leachate management	treatment effectiveness	-24 72	-C	-3	moderately negative change/impacts
	water quality impact	-48 96	-D	-4	significant negative change/impacts
Gas emissions	methane extraction	-32 96	-C	-3	moderately negative change/impacts
	air quality impact	-48 64	-D	-4	significant negative change/impacts
Reclamation	site restoration	24 96	+C	3	moderately positive change/impacts
	community space development	-48 72	-D	-4	significant negative change/impacts

Source: own work.

The comparison (Fig. 5) shows the ES scores between the Radiowo landfill and Kebun Kongok landfill. Based on this, an analysis of the environmental impacts of waste disposal in Indonesia and Poland shows striking differences in environmental management practices and results at the two waste disposal sites. In contrast, Indonesia’s landfills face major environmental challenges, with the majority of their negative impacts indicating an urgent need to improve management practices and interventions to mitigate their adverse effects.

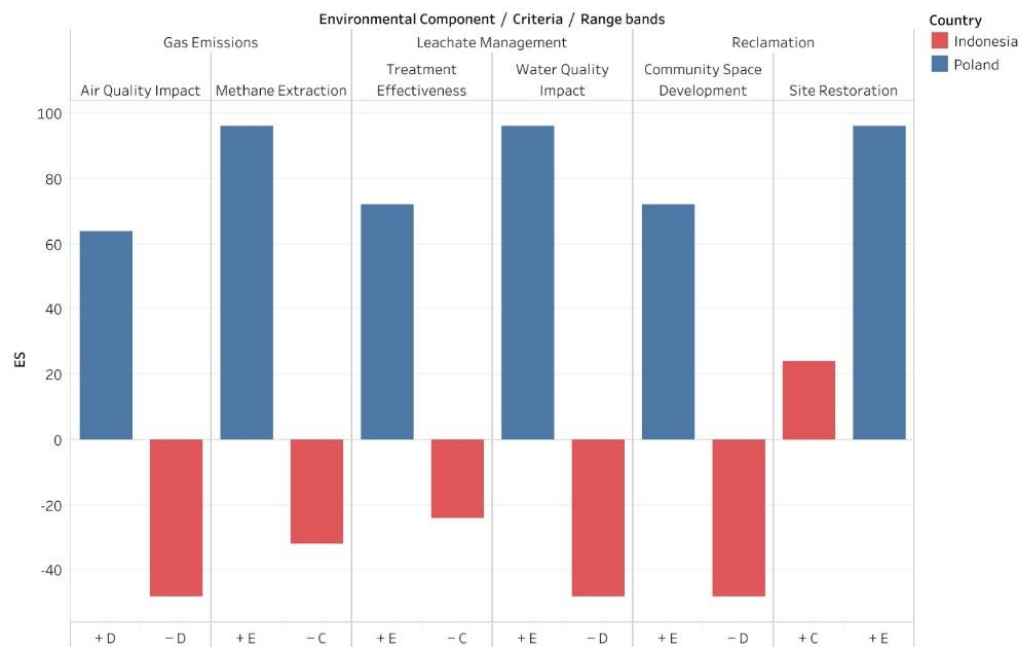


Fig. 5. Environmental impact at Kebon Kongok landfill and Radiowo landfill

Source: own work.

Overall, this comparison highlights that landfill management practices in Poland are much more effective and environmentally friendly, resulting in a significantly positive impact on all assessed components. In terms of gas emissions, Poland scored 96 in managing methane extraction, which affects air quality. They achieve this through a combination of boiler-assisted suction to overcome pipe congestion with real-time infrared analyser monitoring and precise sample quantification of methane emissions. This approach provides crucial data on biogas composition. Additionally, the Radiowo landfill incorporates a natural sealing mechanism that involves insulating materials and integrates a layer of high-density polyethylene (HDPE) foil for enhanced containment. Gas extraction is ingeniously achieved through a passive vertical healthy system that is meticulously designed to effectively capture methane emissions. Vertical collection wells, which are a prevalent and efficient technology for capturing landfill gas (LFG) generated through waste decomposition, enable a comprehensive assessment of the distinct concentration levels of individual biogas components from each well (Kim, Yoshida, Matsuo, Tojo & Matsuo, 2009; Wang & Achari, 2012; Zheng, Rowe & Feng, 2018). Conversely, Indonesia's approach to methane gas capture exhibits dual-pipeline systems by placing vertical and horizontal pipelines within landfill infrastructures. However, these systems are prone to landfill fire accidents (Wahyono, 2015; Ikbāl, 2020).

In contrast, Indonesia scored the lowest in leachate treatment (–24) since the Kebon Kongok landfill causes a series of pond constructions in a tiered system. There are three ponds: anaerobic ponds, facultative ponds and maturation ponds, including monitoring wells to access the potential leachate contamination to groundwater. Besides, the drawback of the pond system is that it is prone to leaks due to cracks in the dividing walls. In fact, improper leachate management can significantly threaten groundwater and surface water quality, as the liquid forms when water percolates through the waste, posing a severe risk to groundwater and nearby water bodies (Vaverková, 2019). Additionally, Indonesia is a tropical country where the rainy season lasts about six months from October to March, which translates into a high potential to produce high amounts of methane and leachate during this period. Although the dry season is expected during this time, different regions in Indonesia may experience rainy seasons in months outside of the mentioned period. The country's average humidity remains high even in the dry season. As a result, leachate and gas are continually produced from landfills throughout the year (Emalya et al., 2020).

Compared to Indonesia, Poland scored 96 and 72 in water quality impact and treatment of the leachate, respectively. The Radiowo landfill implements a carefully designed leachate management system that resembles a multi-stage “hydraulic symphony” and a complex network of reservoirs that regulate water movement, ensuring optimal recirculation within the landfill ecosystem. Trench linings and reservoirs are created to protect the flow of leachate water. Here, four leachate purification actions – geochemical, biochemical, physical and biophysical – are carefully regulated. Absorption, ion exchange, dilution and biochemical reactions take centre stage, culminating in a significant improvement in leachate quality. In particular, mechanical filtration in the aeration and saturation zone is vital in improving water quality by removing larger particles. Moreover, Poland has also implemented a sophisticated drainage system with finger drains, retention reservoirs and dedicated circulation networks for rainwater to manage leachate and gas impact on the environment.

The only environmental component in which the Kebon Kongok landfill in Indonesia scored above minus (48) was on-site restoration. This is because they have implemented a multi-stage process for reclaiming the landfill. This process includes conducting waste management and compaction with layers that are each 60-centimetre thick, resulting in a total compacted depth of 2.4 m. They also daily backfill soil with a thickness of 15 cm to form a single “cell”. After three months, the daily cover thickness is adjusted to 60 cm with the goal of achieving an annual accumulation rate of 2.4 m. On the other hand, the Radiowo landfill in Poland scored (96) in land restoration. This is due to extensive remedial projects that have been implemented. These projects include slope stability and environmental protection measures such as meticulous landfill contour design, the construction of protective berms and vertical bentonite barriers, the implementation of an active degassing strategy, the establishment of technical highways for efficient access and monitoring and the use of a mineral cover system. Additionally, a biological slope reclamation project utilising compost was also undertaken.

CONCLUSIONS

The comparative analysis of landfill practices in Poland and Indonesia, represented by the Radiowo landfill in Poland and the Kebon Kongok landfill in Indonesia, exhibits significant geographical and operational distinctions. While the Radiowo landfill is located near urban areas and environmentally protected zones and employs a sanitary landfill approach, the Kebon Kongok landfill operates in a rural setting and faces challenges associated with open dumping. This research, employing three key environmental component variables – leachate management, gas emissions and reclamation – highlights significant discrepancies in their respective environmental outcomes.

Utilising the Rapid Impact Assessment Matrix (RIAM), this research provides a thorough evaluation of each component's impact on landfill sites in both countries, presenting a clear contrast in their environmental management effectiveness. The comparative study of landfill practices between Poland and Indonesia elucidates significant disparities in environmental management and impacts, highlighting the efficacy of Poland's strategies and the challenges encountered by Indonesia.

In Poland, the evaluation scores indicate a highly effective landfill management system. Specifically, the components of leachate management are water quality impact (96), gas emissions control with methane extraction (96) and site reclamation in site restoration (96). Poland's advanced leachate treatment technologies, including a multi-stage purification process and sophisticated drainage systems, ensure high water quality and effective leachate containment. Additionally, Poland's methane extraction methods, which integrate real-time monitoring and advanced containment strategies, demonstrate a strong commitment to mitigating greenhouse gas emissions. The country's reclamation efforts further underscore its environmental stewardship, with successful site restoration projects reflecting high efficacy and positive environmental impacts. These results reflect Poland's commitment to sustainable landfill management, which not only mitigates negative environmental consequences but also enhances overall ecological health, establishing a benchmark for effective landfill operations on a global scale.

In contrast, the landfill practices in Indonesia, as exemplified by the Kebon Kongok landfill, reveal substantial environmental challenges. The RIAM analysis scores for Indonesia indicate negative impacts across several criteria. The adverse impacts on treatment effectiveness (–24) and water quality (–48) signify severe inefficiencies and detrimental environmental effects. Furthermore, the poor management of methane extraction (–32) and air quality impact (–48) exacerbate the landfill's environmental issues. Although there is a moderate positive outcome in site restoration (24), the overall negative performance indicates critical deficiencies in Indonesia's landfill management practices, particularly in leachate management and gas emissions control. Indonesia's reliance on a series of pond constructions for leachate treatment, which are prone to leaks and cracks, poses significant risks to groundwater and surface water quality. Furthermore, the dual-pipeline system for methane gas capture in Indonesian landfills is less effective and increases the risk of landfill fires. Despite some positive outcomes in site restoration efforts, the overall environmental impact scores highlight critical deficiencies in Indonesia's landfill management practices.

In conclusion, this research emphasises the critical need to adopt advanced landfill management practices to mitigate environmental impacts. Poland's approach serves as a benchmark for effective landfill management, demonstrating that strategic planning and the integration of advanced technologies can lead to significant environmental benefits. For Indonesia, the findings underscore the necessity of substantial improvements in landfill management practices. By adopting the best practices and technologies demonstrated by Poland, Indonesia can address its environmental challenges and achieve significant improvements in landfill management outcomes. This study contributes to the broader discourse on sustainable waste management practices and provides actionable insights for policymakers and environmental managers in both countries.

Authors' contributions

Conceptualisation: Y.R.L. and L.H.; methodology: Y.R.L. and R.K.; validation: M.G.; formal analysis: Y.R.L. and L.H.; investigation and resources: M.G.; data curation: Y.R.L.; writing – original draft preparation: Y.R.L.; writing – review and editing: Y.R.L. and L.H.

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

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ANALIZA PORÓWNAWCZA PRAKTYKI SKŁADOWANIA ODPADÓW W POLSCE I INDONEZJI

STRESZCZENIE

Badania opisane w artykule dotyczą globalnego wyzwania, którym jest zarządzanie odpadami. Jego celem były określenie różnic w systemach zarządzania składowiskami oraz analizy głównych wyzwań w implementacji efektywnych systemów zarządzania składowiskami w Polsce i Indonezji poprzez porównanie praktyk zarządzania w obiekcie w Radiowie i na składowisku Kebon Kongok. Dane zostały przeanalizowane z wykorzystaniem *rapid impact assessment matrix* (RIAM). W analizach skupiono się na trzech kluczowych obszarach: zarządzaniu gazami, zarządzaniu odciekami oraz rekultywacji składowisk. Według wyników badań na polskim składowisku bardzo skutecznie zarządza się odciekami z wpływem na jakość wody (96), kontroluje emisjami gazów z ekstrakcją metanu (96) oraz przeprowadza rekultywację terenu w systemie przywracania terenu do stanu pierwotnego (96). Do tych celów to składowisko wykorzystuje zaawansowane technologie oczyszczania odcieków oraz systemy drenażowe. Praktyki zarządzania indonezyjskiego składowiska, zgodnie z wynikami badań, cechuje poważna nieskuteczność w niemal wszystkich sektorach; najgorszy wynik dotyczył zarządzania odciekami z wpływem na jakość wody (–48), emisji gazów z wpływem na jakość powietrza (–48) oraz rekultywacji terenu w rozwijaniu przestrzeni dla społeczności (–48). Badanie ma wkład w dyskurs na temat zrównoważonego zarządzania odpadami, dostarczając praktycznych wskazówek dla decydentów i menedżerów środowiskowych.

Słowa kluczowe: zarządzanie składowiskiem odpadów, RIAM, zarządzanie gazami, zarządzanie odciekami, rekultywacja

THE MAIN STRENGTH MATERIAL PARAMETERS OF DEFORMABLE CEMENT ADHESIVES

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ABSTRACT

The deformable cement adhesives types C2S1 and C2S2 are usually used to glue ceramic slabs onto so-called critical substrates (other than concrete), including under changing weather conditions. The declared strengths of these adhesives attached to substrates can be found in the manufacturer's standards and declarations. The use of cement adhesives on surfaces other than concrete or in other applications, such as a lightweight heated floor system (LHFS), should meet safety standards. To determine this, basic strength parameters for deformable adhesives, which have not been specified until now, need to be set. For this purpose, many analyses were performed, such as tensile and compressive strength tests, as well as the measurement of displacements in the thermal chamber, using, for example, digital image correlation and extensometric techniques. It was possible to define the main strength parameters of deformable adhesives, such as Young's modulus (E), Poisson's ratio (ν) and linear thermal expansion coefficient (α). These multiple measuring techniques were able to authenticate the obtained results, determining the maximum compressive strength of deformable adhesives, as well as longitudinal and transverse deformations. The research material parameters E , ν and α can be used for the calculation of LHFS with a heating coil, as well as for other building partitions or on critical substrates (different from concrete), using some of the many numerical methods available.

Keywords: Young's modulus, Poisson's ratio, thermal expansion coefficient, deformable cement adhesives

INTRODUCTION

One of the many loads that occur in a lightweight heated floor (generated by the heating system) or in an ETICS system (influenced by solar heat) are thermal actions as well as standard loads – imposed and self-weighted. Both of these systems are considered lightweight because the thermal insulation is not covered with a thick layer of concrete, but directly with an adhesive and mesh layer, and then with ceramic tiles, plaster or other types of thin floor covering, as described in the literature (Nordic Council of Ministers [NT], 2001; Elektra Kardo, 2018; Flooré, 2019). Under the influence of the mentioned loads, stresses and deformations occur inside the floor/wall structure. The most important layer in the entire section of the lightweight floor or wall is the adhesive mortar. It connects the top and bottom layers of a Lightweight Heated Floor System (LHFS).

It has to transfer various types of internal stresses arising from external loads, including thermal actions. To determine these stresses, a number of experiments had to be performed as described in papers by Karpiesiuk

(2020a, 2020b) and Karpiesiuk and Chyzy (2020a, 2020b). In order to confirm whether the experimentally determined strength test results meet the load capacity criteria of the LHFS component materials, numerical calculations must be performed. These can be realised using the Finite Element Method (FEM) or other numerical methods. To apply these methods, the strength parameters of the materials contained in the LHFS are necessary. The parameters of the ceramic tile, glass fibre mesh or thermal insulation are written in Table 1 together with a list of literature.

Table 1. The strength material parameters from the literature

Material	Young's modulus (E) [MPa]	Thermal expansion (α) [$10^{-6} \cdot K^{-1}$]	Poisson's ratio (ν) [-]
Ceramic tile	50 000	8	0.16
Anisotropic glass fibre mesh type E, GFRP	60 000–70 000	4.7	0.22
XPS 300	13–15	70–75	0.20
EPS 200	7.8	55	0.17

Source: Shulmeister (1997); Artemenko (2003); Wambua, Ivens and Verpoest (2003); Perepelkin (2005); Dow Chemical Company (2008, 2014); Piekarczyk, Kata, Lis and Galos (2008); Fibran (2010); Elragi (2012); Padade and Mandal (2012); European Committee for Standardisation [CEN] (2014, 2015, 2016a, 2016b).

The material parameters of the deformable adhesives type C2S1, C2S2 and their composite with a glass fibre mesh – such as Young's modulus, thermal expansion and Poisson's ratio, which bond the ceramic floor to the thermal insulation – are not available in the literature. These parameters are essential for numerical calculations using the finite element method (FEM). The determination of these material parameters can be achieved by several test methods. Ideally, these parameters should be confirmed using multiple methods to verify the obtained data.

MATERIAL AND METHODS

The materials tested are deformable C2S1 and C2S2 adhesives. Various tests were performed primarily to determine material parameters such as Young's modulus, Poisson's ratio and the thermal expansion coefficient of the C2S1 and C2S2 deformable adhesives. Additionally, the compressive strengths of these adhesives were tested. The research was conducted in the laboratories of the Białystok University of Technology and the Kraków University of Technology.

Young's modulus and Poisson's ratio of C2S1 and C2S2 adhesives were determined using the following methods:

- the tensile strength of C2S1 adhesive was tested using dumb-bell test specimens and extensometers;
- the compressive strength of the C2S1 and C2S2 adhesives were tested using cylindrical samples and extensometers.

The thermal expansion coefficient of the C2S1 and C2S2 adhesives were tested using the following methods:

- the adhesives were tested using the Digital Image Correlation (DIC) method, placing their rectangular samples in a thermal chamber;
- the adhesives were tested using an inductive sensor, placing their cylindrical samples in the special author's thermal chamber.

Research to determine the tensile strength data for Sika Ceram 255 cement adhesive mortar C2S1 was performed in a laboratory of the Białystok University of Technology.

Dumb-bell test specimens of C2S1 adhesive was used for these tests, performed following the ISO 527-2:2012 standard (International Organisation for Standardisation [ISO], 2012). One of the four specimens and its dimensions is shown in Figure 1. The measurement base was 20 mm.

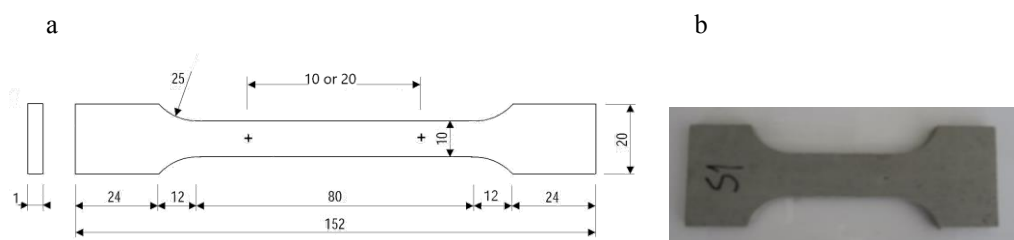


Fig. 1. Dumb-bell test specimens: a – samples dimensions [mm], according to EN ISO 527-2 standard (ISO, 2012); b – sample of C2S1 adhesive

Source: own work.

A dynamic two-axis MTS 858 Mini Bionix testing machine was used to research the displacement measurements of C2S1, which worked with Instron 2620 and Epsilon 3542050M-025-HT1 extensometers (Fig. 2). The dependence of longitudinal deformation (ϵ_m) on tensile stress was studied on three samples.

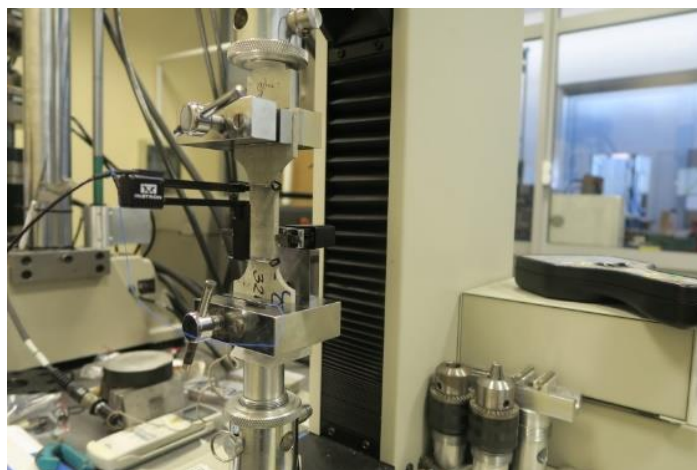


Fig. 2. Measurement of longitudinal deformation (ϵ_m) and transverse deformation (ϵ_n) using extensometers

Source: own photo.

The experimental compressive strength of the C2S1 and C2S2 adhesives, as described in (Karpiesiuk & Chyzy, 2020a), allows for determining the stress-deformation functions of the C2S1 adhesive mortar (specifically Sika Ceram 255) and C2S2 adhesive mortar (specifically BASF Flex-mortel), along with their Young's modulus and Poisson's ratios. The experimental research was supported by mathematical verification calculations. The article (Karpiesiuk & Chyzy, 2020a) provides detailed information on the preparation and execution of this research.

The research on the linear expansion coefficient was carried out in two stages. The first, preliminary stage, was performed at the Białystok University of Technology, using the digital image correlation (DIC) method in the Aramis system, as described earlier in (Karpiesiuk, 2020a). The next stage was performed at the Kraków University of Technology, using an inductive sensor to measure material displacements.

In the preliminary studies for determining the linear thermal expansion coefficient of C2S1 Sika Ceram and C2S2 BASF Flex-mortar adhesive mortars (using the DIC method), $10 \times 10 \times 80$ mm samples were used. They were placed in an MTS 651.05E-02 environmental chamber (Fig. 3), where cooperation with the DIC set was visible. The samples were covered in a random pattern of coloured spray paint. The tests started at 20°C and ended at 70–80°C. The first displacement measurement was conducted at 30°C. The testing time of each specimen was 1–3 h.

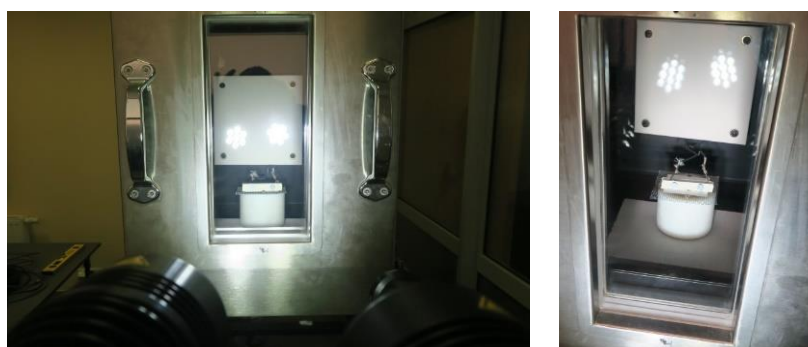


Fig. 3. ARAMIS 3D 4M vision set and MTS 651.05E-02 thermal chamber to research the thermal expansion coefficient (α) of the C2S1 adhesive

Source: own photos.

The second part of the research on the thermal expansion coefficient (α) includes the experiments carried out by Zajac (2018) on cylindrical specimens. It was conducted in a special thermal chamber using WA-10 induction sensors for displacement measurement and connected to a computer equipped with Catman Easy 3.1 data acquisition software. Based on these experiments, verification tests of the coefficient α were performed at the Kraków University of Technology for deformable adhesives. For this purpose, cylindrical samples with a diameter of 28 mm and length of 120 mm were prepared from C2S1 and C2S2 adhesives, as shown in Figure 4. The tests started at 0°C and ended at 80°C.

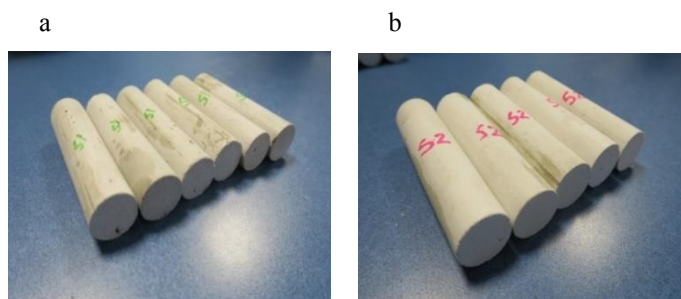


Fig. 4. Cylindrical samples of C2S1-S1 adhesive (a) and C2S2-S2 adhesive (b)

Source: own photos.

RESULTS AND DISCUSSION

The main objective of the tensile strength research, using dumb-bell samples of C2S1 adhesive, was to determine Young's modulus (E). For this purpose following formula was used:

$$\sigma = \frac{F_r}{A}, \quad (1)$$

where:

σ – stress in the adhesive [MPa],

F_r – tensile force [N],

A – cross-section of the sample [mm²].

The quadratic functions characterising the dependence of stress (σ) on longitudinal deformation ($\mathcal{E}_m$) at the tensile strength of adhesives were determined from Eq. (1).

Young's longitudinal modulus of elasticity was determined using Hooke's law:

$$\sigma = E \cdot \mathcal{E}. \quad (2)$$

An example of C2S1 adhesive stress dependence on the longitudinal deformation in extensometer research is shown in Figure 5. In the test, the three samples of the C2S1 adhesive averaged a maximum tensile stress ($\sigma_{\max \text{ avg}}$) of 1.35 MPa, average longitudinal tensile deformation ($\mathcal{E}_m$) of 0.0006 and average elasticity modulus ($E_{c \text{ avg}}$) of 5,950 MPa.

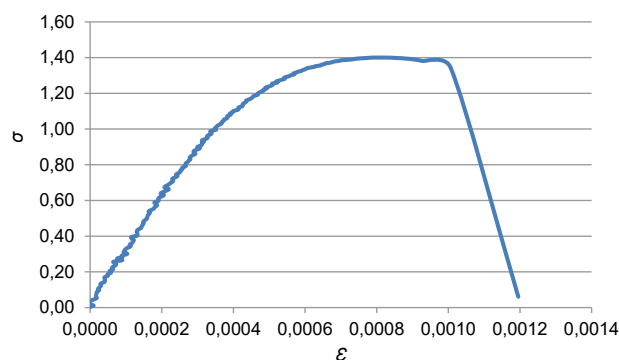


Fig. 5. Dependence of stress (σ) to the longitudinal deformation ($\mathcal{E}$) one of the C2S1 adhesive

Source: own work.

Four different function graphs were made to determine the values of Young's modulus of deformable C2S1 and C2S2 cement adhesives in the article (Karpiesiuk & Chyzy, 2020a). The graphs of the $S1$ and $S2$ functions were defined only based on experimental tests of the compressive strength of cylindrical samples. The graphs of the $S1$ *Evola* and $S2$ *Evola* functions are additionally based on the mathematical formulas, the so-called "Madrid parabola" (Eqs 3 and 4), which verified the experimental results through mathematical analyses. The graphs of the four functions $S1$, $S2$, $S1$ *Evola* and $S2$ *Evola* are shown in Figure 6. $S1$ *Evola* and $S2$ *Evola* were accepted as the final results (i.e., those after mathematical verification, considering them to be closest to the truth).

For calculating compressive stress in cement adhesive mortar C2S1 following formula was used:

$$\sigma_{S1} = 15.5 \left[1 - \left(1 - \frac{\varepsilon_{S1}}{0.0051} \right)^2 \right], \quad (3)$$

where:

σ_{S1} – compressive stress in C2S1 adhesive, corresponding to the deformation ε_{S1} ,

ε_{S1} – deformation of C2S1 adhesive from the research.

For calculating compressive stress in cement adhesive mortar C2S2, the following formula was used:

$$\sigma_{S2} = 13.7 \left[1 - \left(1 - \frac{\varepsilon_{S2}}{0.0126} \right)^2 \right], \quad (4)$$

where:

σ_{S2} – compressive stress in C2S2, corresponding to the deformation ε_{S2} ,

ε_{S2} – deformation of C2S2 adhesive from the research.

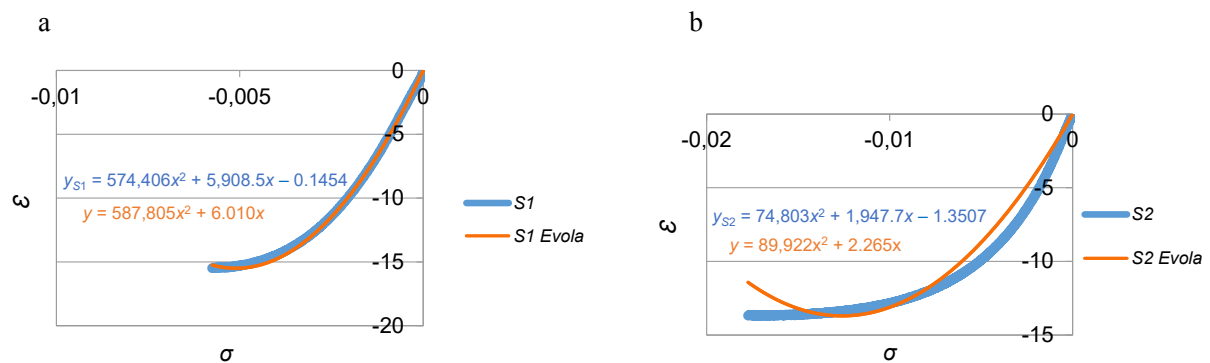


Fig. 6. Graphs of calculated functions S1 and S1 Evola (a) compared to functions S2 and S2 Evola (b)

Source: Karpiesiuk and Chyzy (2020).

Knowing the deformation and stress of the cement adhesives C2S1 and C2S2, these longitudinal elasticity modules were designated: E : E_{S1} equals 6,000 MPa and E_{S2} equals 2,300 MPa.

Poisson's ratio is the absolute value of the ratio of the transverse deformation to the corresponding axial deformation resulting from a uniformly distributed axial stress below the proportional limit of the material. It is described using following formula:

$$\nu = -\frac{\varepsilon_n}{\varepsilon_m}. \quad (5)$$

The coefficient ν is estimated by conducting tests and subjecting it to a tensile or compressive force, according to the American standard ASTM E132-17 (ASTM International [ASTM], 2017), in the uniaxial state of stress. In the calculations, the arithmetic mean value of the Poisson's ratio in the elastic phase of the compressive stress of the cement adhesives from each sample was adopted, whose characteristics are close to linear and reach stable numerical values. Examples of the dependence of stress from the quotient of the ratio transverse to longitudinal deformation (ν) C2S1 adhesive in tests with the extensometers are shown in Figure 7.

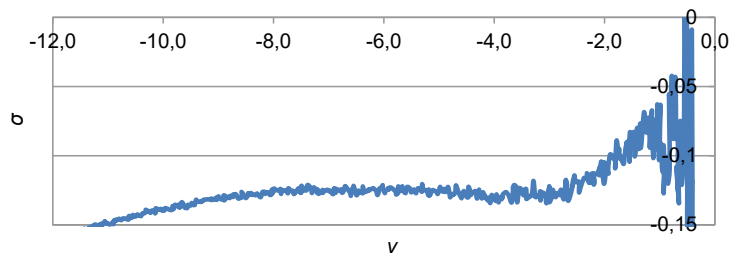


Fig. 7. The dependence of stress (σ) from the quotient of transverse to longitudinal deformation (ν) in the cement adhesive C2S1

Source: own work.

Table 2 presents the longitudinal modulus of elasticity (E_{avg}) from a paper by Karpiesiuk and Chyzy (2020a), as well as the results of maximum compressive stresses and Poisson's ratio (ν). Additionally, preliminary data of Young's modulus (E) for each type of adhesive are included, based solely on the experimental results without mathematical analyses. The full research and mathematical analysis are presented in the paper by Karpiesiuk and Chyzy (2020a).

Table 2. Deformable adhesives' mechanical characteristics

Adhesive	Averaged compression strength ($\sigma_{max\ avg}$) [MPa]	Averaged Young's modulus (E_{avg}) [MPa]	Averaged Poisson's ratio (ν_{avg}) [-]
C2S1	15.52	5 900	0.13
C2S2	13.73	1 950	0.15

Source: own work.

The research of the thermal expansion (α_c) of C2S1 and C2S2 adhesives were carried out in a temperature range of 30–80°C. Underfloor heating is a low-temperature heating system; therefore, the sufficient maximum temperature measurement range is 50°C. However, for research purposes and the possibility of other applications of cement adhesives where the impact temperature difference is higher (e.g., terraces and balconies), the measurement range was increased to 80°C. The results of the coefficient α_c were determined from Eq. (6), found in standard ISO 527-2:2012 (ISO, 2012):

$$\alpha_c = \frac{\Delta L}{L_0 \cdot \Delta T}, \quad (6)$$

where:

α_c – thermal expansion [-],

ΔL – the length of the sample increase between the temperature intervals [mm],

L_0 – the length of the sample base at ambient temperature (20°C) [mm],

ΔT – temperature increase [°C].

The dependence of displacement (d_s) on research time (t) is shown in Figures 8 and 9 (C2S1 and C2S2 adhesives). The measurement base was 60 mm. The calculations were performed at temperature intervals of 10°C increments, from 30°C to 70°C. The two-colour differences, marked in Figures 8 and 9, show the two displacement results of three tested adhesive samples.

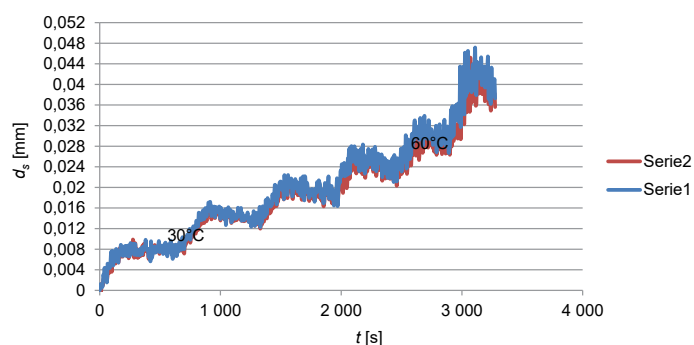


Fig. 8. The dependence of displacement (d_s) to time (t) for C2S1 adhesive samples

Source: own work.

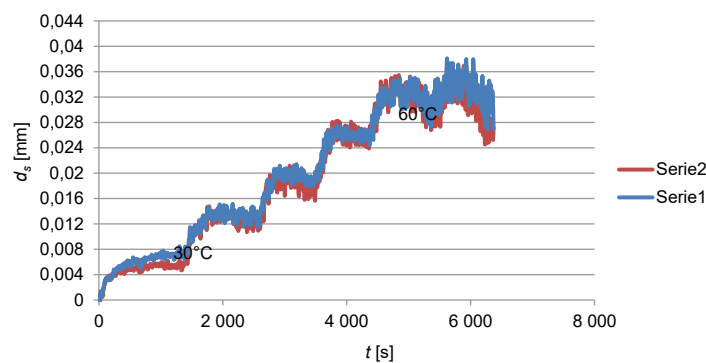


Fig. 9. The dependence of displacement (d_s) to time (t) for C2S2 adhesive samples

Source: own work.

Measurements verifying the thermal expansion coefficient (α) of cylindrical samples, performed at the Kraków University of Technology, in a temperature range 0–80°C of C2S1 and C2S2 adhesives, are shown in Figure 10. The calculation of the average values of the coefficient α was performed based on Eq. (6) and determined the subsequent trend lines (Fig. 10). The results summaries of rectangular and cylindrical samples of C2S1 and C2S2 adhesive are shown in Table 3.

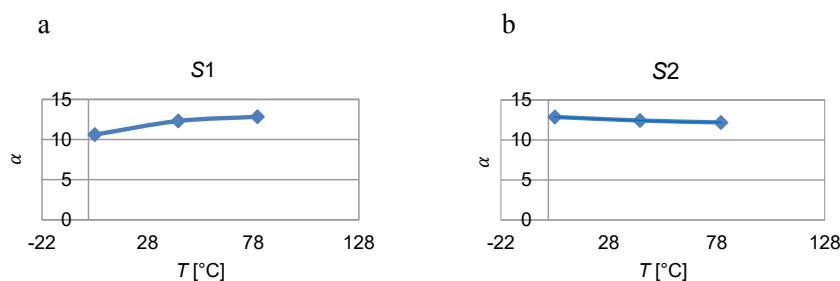


Fig. 10. Temperature (T) dependence on the coefficient of linear expansion (α) of C2S1 adhesive (a) and C2S2 adhesive (b)

Source: own work.

In this paper, material parameters such as Young’s modulus (E), Poisson’s number (ν) and thermal expansion coefficient (α) of deformable cement adhesives – C2S1 Sika Ceram 255 and C2S2 BASF Flex-mortar were determined. The C2S1 adhesive Young’s modulus at the compressive strength test was 6,000 MPa, while the tensile strength was 5,950 MPa. For the coefficient α of two adhesives, on rectangular samples – using the DIC method and on cylindrical samples using an inductive sensor – the results were similar, considering the small value of α shown as 10^{-6} (Table 3).

Table 3. Average results of linear expansion coefficient ($\alpha_{c \text{ avg}}$) of C2S1 and C2S2 adhesive in Białystok and Kraków laboratories [$10^{-6} \cdot \text{K}^{-1}$]

Adhesive	Results from Białystok laboratory	Results from Kraków laboratory	Averaged results from both laboratories
C2S1	10.0	11.7	10.85
C2S2	13.0	13.6	13.30

Source: own work.

The standard EN 12004:2007+A1:2012 (CEN, 2007) gives many characteristics for cement adhesives used for tiles. Two of the most important adhesive characteristics are adhesion and deformability. The highest adhesion is marked in the standard with class C2, and deformability is marked with class S1 or S2. Class C2 means that the adhesion of the tested adhesive to a flat, even surface (e.g., concrete) must be either greater than or equal $1.0 \text{ N} \cdot \text{mm}^{-2}$. This adhesion value indicates the tensile strength perpendicular to the face of the adhesive mortar, attached to the substrate of the concrete slab according to the standard EN 1348:2007 (CEN, 2007). Classes S1 and S2 inform about the deformability of cement adhesives, where class S1 means deformable adhesives within 2.5–5 mm and class S2 indicates the highest deformability greater than 5 mm, according to standard EN 12002:2010 (CEN, 2010). Differences in the deformability of cement adhesives from 2.5–5 mm (i.e., up to 100%) allow manufacturers to produce them with higher or much lower quality. Similarly, adhesion, defined by the standard at a minimum of 1 MPa, allows the manufacturer to set the adhesion of the adhesive at a minimum value or well above the minimum value. The share of aggregate and cement in cement adhesives is approximately 90% (Leone, 2018), hence the value of adhesion and deformability is determined by various additives improving the “flexibility” and other features of cement adhesives. This means the client can find adhesives with the same marking but higher or lower quality for sale.

CONCLUSIONS

The strength parameters of cement adhesive types C2S1 and C2S2 were defined, such as Young’s modulus (E), Poisson’s ratio (ν) and the coefficient of linear thermal expansion (α). Many of the measurement techniques used allowed the verification of the obtained results. Additionally, the maximum compressive strength of deformable adhesives, longitudinal and transverse deformations were determined. This data can be used for the calculation of lightweight heated floor systems (LHFS) with a heating coil, as well as for all other building partitions such as balconies, patios, stairs and other horizontal or vertical surfaces on critical substrates, using one of the many numerical methods.

It is worth noting that deformable cement adhesives of C2S1 and C2S2 from specific manufacturers were tested. The standards EN 1348:2007 (CEN, 2007) and EN 12002:2010 (CEN, 2010) allow for significant discrepancies in the quality of these adhesives. For example, the deformation value in C2S1 adhesive may vary by up to 100% (permissible deformation is 2.5–5 mm). Therefore, the quality and material parameters of the same type of deformable adhesive from a different manufacturer may differ. Hence, it is worth repeating

the tests using the same type of deformable adhesives but from other manufacturers. In this way, it is possible to check how big the differences, and whether they exist, are between strength material parameters E , ν and α for many different manufacturers.

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NAJWAŻNIEJSZE WYTRZYMAŁOŚCIOWE PARAMETRY MATERIAŁOWE ODKSZTAŁCALNYCH KLEJÓW CEMENTOWYCH

STRESZCZENIE

Odkształcalne kleje cementowe typu C2S1 i C2S2 najczęściej są stosowane do klejenia płyt ceramicznych na tzw. podłożach krytycznych (innych niż beton), jak również w zmiennych warunkach atmosferycznych. Deklarowane wytrzymałości tych klejów mocowanych do podłoża betonowych można znaleźć w normach i deklaracjach producenta. Stosowanie klejów cementowych na powierzchniach innych niż beton lub w innych zastosowaniach, np. w systemie lekkiej podgrzewanej podłogi (LHFS), powinny spełniać normy bezpieczeństwa. Aby się o tym przekonać, należy ustalić podstawowe parametry wytrzymałościowe klejów odkształcalnych, które nie zostały dotychczas określone. W tym celu przeprowadzono wiele badań, m.in. wytrzymałości na rozciąganie i ściskanie, a także pomiar przemieszczeń w komorze termicznej, wykorzystując m.in. cyfrową korelację obrazu i techniki ekstensometryczne. Dzięki temu możliwe było określenie głównych parametrów wytrzymałościowych klejów odkształcalnych, takich jak: moduł Younga (E), współczynnik Poissona (ν) oraz liniowy współczynnik rozszerzalności cieplnej (α). Te wielorakie techniki pomiarowe pozwoliły na uwiarygodnienie uzyskanych wyników, określenie maksymalnej wytrzymałości na ściskanie klejów odkształcalnych oraz odkształceń wzdłużnych i poprzecznych. Parametry materiału badawczego E , ν i α można wykorzystać do obliczeń LHFS z węzownicą grzejną, a także dla innych przegród budowlanych lub na podłożach krytycznych (innych niż beton), wykorzystując niektóre z wielu metod numerycznych.

Słowa kluczowe: moduł Younga, współczynnik Poissona, współczynnik rozszerzalności cieplnej, odkształcalne kleje cementowe

A COMPARISON OF PROFESSIONAL LIABILITY OF ARCHITECTS IN POLAND AND SWEDEN

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ABSTRACT

In Poland, the title of architect is a regulated profession, and many parameters must be met in order to obtain a construction license in the architectural specialty. On the other side of the Baltic Sea, in Sweden, where being an architect is also a regulated profession, the responsibility of this profession presents itself differently. The comparison of Poland and Sweden in terms of architectural professional liability aims to analyse how the architectural design process can influence the quality of architecture and the relationship between the architect and investor. By analysing these relations, one can observe the tendencies in architectural styles and the cost of building. The comparison of these two countries is based on the analysis of granting the architectural title and the required education. Another important factor in the comparison is the matter of liability. In Poland, an architect has civil responsibility, while in Sweden, an architect does not. The fact that the same architect works throughout all phases of the project in Poland allows for better implementation of the designer's assumptions. In contrast, in Sweden, where phases of the project circulate between different architects, the creator of the concept has limited control over the end result. These differences have a big impact on the quality of architecture in general.

Keywords: architecture, Poland, professional liability, regulated profession, Sweden

INTRODUCTION

The professional responsibility of an architect carries with it many responsibilities and privileges. In his doctoral dissertation, Michał Leszczyński writes: “An integral part of thinking about the architectural profession is to cover not only the broad, but also the deep optics of its impact. Design is linked to a long-term perspective” (Leszczyński, 2021, p. 5).

In Poland, the title of architect is a regulated profession, and many parameters must be met in order to obtain a construction license in the architectural specialty. On the other side of the Baltic Sea, in Sweden, where being an architect is also a regulated profession, the responsibility of this profession presents itself differently. The comparison of Poland and Sweden in terms of architectural professional liability is to analyse how the architectural design process can influence the quality of architecture and the relationship between the architect and investor. By analysing those relations, one can observe the tendencies in architectural styles and the cost of building.

Tobias Olsson, Director of the Swedish Association of Architects, says: “If anyone starts calling themselves an architect, it marginalises the competence that architects have” (Westrin, 2023). This shows the importance of analysing the role of an architect in a project and their professional liability to maintain the highest possible quality of architecture.

In his work, Tomasz Taczewski, President of the National Council of the Chamber of Architects, points to the difference between Poland and Sweden in terms of architectural profession: “The practice of the architectural profession in a united Europe, prior to its expansion to include new countries, was founded on self-governing architectural organisations [own translation]” (Taczewski, 2020). Tomasz Taczewski mentions self-governing organisations that influence access to the profession in Austria, Belgium, France, Germany, Greece, Italy, the Netherlands, Ireland, Luxembourg, Portugal, Spain, the United Kingdom and Poland. He notices that they function in Austria, Belgium, France, Germany, Greece, Italy, the Netherlands, Ireland, Luxembourg, Portugal, Spain and the United Kingdom. Similarly, in Poland, these organisations can influence access to the profession. However, he mentions a different situation in Denmark, Finland and Sweden. “The dissimilarity of the solutions adopted in Scandinavian countries should be attributed to the fact that they are relatively small countries with a high architectural culture based on good manners [own translation]” (Taczewski, 2020).

MATERIAL AND METHODS

The methods applied are:

1. A description of the process of granting an architect’s title and professional liability in Sweden, based on required education and obtaining a professional title.
2. A description of the process of granting an architect’s title and professional liability in Poland, based on required education and obtaining a professional title.
3. A SWOT analysis showing tendencies in architectural styles and cost of building, based on two approaches to professional liability in Poland and Sweden, based on the authors’ professional experiences in those two countries (in architectural offices, working for an investor and constructor).

A SWOT analysis started to germinate in the early 1950s, “an era known as *the war on bigness* between the US Government and large corporations” (Puyt, Lie & Wilderom, 2023, p. 3).

The main purpose of this method is “to push the known strengths, reduce weaknesses, exploiting the opportunities and having contingency plans to minimise threats. There unit of measure several edges and edges of victimisation SWOT Analysis for private development. It’s smart for your success and betterment” (Singh & Sayeed, 2021, p. 19).

The purpose of the SWOT division is to help categorise tendencies by showing which ones contribute to strengths, such as the quality of architecture, and which ones may pose future risks to that quality. It can also indicate which areas require a more careful examination and analysis due to different threats and potential issues.

Granting an architectural title in Sweden

The title *architect* is not one that is protected in Sweden. This means that anyone can call themselves an architect. However, employers who hire an architect expect them to have at least a bachelor’s degree, with first- and second-level studies lasting five years.

The term *bachelor’s degree* has not been used incorrectly here because, unlike in Poland, graduation from a technical college in Sweden (e.g., Chalmers Tekniska Högskola in Gothenburg or KTH – Kunliga Tekniska Högskola in Stockholm) with a specialisation in architecture does not result in an engineering degree.

In order to obtain an engineering degree (Master of Engineering or Bachelor of Engineering) one must complete a special, separate technical programme offered by the chosen Technical University (KTH Royal Institute of Technology [KTH], 2023).

Once an architect has completed university studies, a person can obtain the title of SAR (Swedish: *Sveriges Arkitekter*) after working for a period of 24 months in an architectural office as an architect in Sweden or a country in the European Union. The SAR title is conferred by Sveriges Arkitekter (The Swedish Association of Architects – SAR), “a professional union and interest organisation that promotes the common cause of Swedish architects”. (Sveriges Arkitekter [n.d. a].

Table 1. Titles granted by Sveriges Arkitekter

Original title	Practical translation in English
arkitekt SAR/MSA	architect
landskapsarkitekt LAR/MSA	landscape architect
arkitekt SIR/MSA	architect (engineer)
planeringsarkitekt FPR/MSA	urban planner

Source: Sveriges Arkitekter [n.d. b].

These titles are protected professional and membership titles that indicate that an architect has architectural training and is a member of the Swedish Association of Architects: SAR stands for The Swedish Association of Architects; LAR for The Swedish Association of Landscape Architects; SIR for The Swedish Association of Sweden’s Engineers; FPR for The Swedish Association of Physical Planners.

Architects’ professional liability in Sweden

What is an architect’s profession like, in practice, in Sweden? Does the architect take any responsibility for the project? What happens in case of a mistake? An architect in Sweden typically handles various stages of urban planning, conceptual design, obtaining building permits and overseeing the construction project. Once the construction project is handed over to the investor, the investor and contractor continue to develop the project with a more detailed design and execution, without the architect’s direct involvement. The construction project, which includes descriptions of materials and detail drawings, can be changed as long as the change does not significantly affect the building permit. This means that the architect most often does not decide on the details, materials or quality of finish, does not classify changes in the project as significant or non-significant and does not make changes to the project during implementation. Most often, at the very end, they perform an as-built design confirming the existing state of the newly built building.

In Sweden, architectural offices have copyrights, but often allow the possibility for the investor to continue with a different office during the upcoming phase of the drawing process. This is why it is a very common practice in Sweden for someone else to draw the concept, another person to draw the construction project and yet another person to draw the as-built project. An employed architect usually assigns the economic copyright to his or her employer through their employment contract. Of course, there are situations where one architect or architectural office designs all stages. The factors that make this possible are usually:

- recognition and reputation of the architect;
- a good relationship between the architect and the contracting authority;
- price;
- securing with an appropriate contract/order.

Otherwise, the project circulates between offices, and an office with lesser recognition or conflicts with the investor is less likely to carry out the entire design process. The architectural office, regardless of participation in the further design project, can publish the project to build a resume and must always name all the authors. If an architect makes a design error, as defined in the Swedish Construction Law (Boverkets byggregler, 2011; Boverket, 2023), such as failing to assign a class to a fire door or failing to provide necessary rules to accommodate the needs of disabled individuals, the investor can claim compensation from the office employing the architect. The investor will then be paid compensation that is equal to the costs incurred by the client as a result of the architect's error.

Granting an architectural title in Poland

In Poland, similar to Sweden, being an architect is not a protected title. This means that anyone can refer to themselves as an architect. However, just like in Sweden, the title is regulated. To be granted the title of Master of Engineering in Architecture, a person must complete a 5–6 year architectural programme that adheres to ministerial standards.

Once an architectural student has completed university, the person can start working to obtain the title granted by the Izba Architektów Rzeczypospolitej Polskiej (Chamber of Architects of the Republic of Poland – IARP). The IARP is a professional self-government of architects, which consists of 17 organisational units that are a part of the Krajowa Izba Architektów (National Chamber of Architects).

In order to become a member and gain a professionally protected title, one must: “obtain a construction license within the architectural specialty without limitations, which entitles one to the title of architect of the IARP, one must complete a first- or second-cycle (or single-degree) course of study with a major in architecture and obtain a master's degree in architecture. You must also complete an apprenticeship, the duration of which, in the case of construction authorisations in architectural specialty without limitations, is: one year in drafting projects and one year on-site. The prerequisite for the completion of the apprenticeship is work involving direct participation in designing or performing a technical function on a construction site under the direction of a person with the appropriate construction authorisation or, in the case of an apprenticeship abroad, a person with the appropriate authorisation in the country. It is necessary to take the examination for the construction license in architectural specialty organised by the Qualification Commission of the Chamber of Architects of the Republic of Poland. Depending on your education and the scope of your professional practice, the exam is conducted for construction rights to: designing in a given specialty; directing construction works in a given specialty; designing and directing construction works in a given specialty. The types and forms of construction authorisations in the architectural specialty that can be obtained are listed in Article 14 of the Polish Construction Law” (Izba Architektów Rzeczypospolitej Polskiej [IARP], 2024).

As we can see, the design process and liability in Sweden present themselves quite differently from Poland.

Architects' professional liability in Poland

Unlike in Sweden, the architect assumes civil responsibility for the project for which they are responsible with their architectural license. In the event that the safety of the future user of his completed project is compromised, they may even be held liable for the error before the Krajowy Sąd Dyscyplinarny (National Disciplinary Court) and convicted by sentence.

The responsibility is related to the higher control of the entire design process throughout all phases. Architects designing in Poland have the right to authorship supervision. Author's supervision is a term taken from both the Construction Law (consolidated text Dz.U. 2024 poz. 725, 834) and the Copyright Law (consolidated text Dz.U. 2022 poz. 2509), so its explanation should be based on both legal acts.

The author's supervision of a project is an inalienable right vested in the author, as one of the elements of the catalogue of the author's moral rights, protecting the author's intellectual relationship with the work they have developed. As such, it consists of the ability to control the use and exploitation of one's own work by others.

The two main roles of the architect during the construction process is to:

- ascertain, in the course of construction works, the compliance of the execution with the design;
- agree on the possibility of introducing solutions that are substitutable for those provided in the design, reported by the construction manager or the investor's supervision inspector.

The scope of work performed by the designer at the construction site depends on individual arrangements and also results from the provisions of the applicable law. This results in the fact that other architects cannot work on the project during any of its phases without a granted permission from the architect who is the author of the design.

RESULTS AND DISCUSSION

What are the strengths, weaknesses, opportunities and threats when an architect in Sweden most often ends one's design on a construction project, while an architect in Poland can go through the executive project? Table 2 presents an analysis based on the authors' many years of professional experience in the Polish and Swedish markets.

Table 2. SWOT analysis

S strengths	W weaknesses	O opportunities	T threats
Sweden: Lower construction cost, changes are made faster on-site.	Sweden: Risk of inferior architecture in the form of detail, material quality.	Sweden: Opportunity for faster development of advanced mass production technologies needed in the event of an emergency, higher construction needs.	Sweden: Much more frequent emergence of repetitive, homogeneous architecture that does not relate to the context of the place.
Poland: The same architect throughout all phases of the project allows a better implementation of the designer's assumptions.	–	Poland: The architecture does not aim mainly towards the development of advanced mass production technologies, architects can participate stronger in architectural development.	Poland: Possible higher construction cost, changes need architect's categorisation and approval.
Sweden: The construction process goes faster without the necessary architect's professional opinion on the changes.	Sweden: The practical functional aspect and the fulfilment of the rules prescribed by the building law is the only determinant of the quality of the designed architecture.	Sweden: Greater use of typical solutions in the construction process leads to a smoother construction process, fewer errors and cost savings.	Sweden: Unification of the appearance of cities, streets, buildings, parks. Loss of authorial characteristics.
Poland: Architect's opinion on the changes and making them relevant allows architecture to present higher standards.	–	Poland: The profession of architect is more socially appreciated.	–
–	Sweden: The architect's opinion on the changes and making them relevant does not affect the purely practical functional aspect and the fulfilment of the principles enshrined in the construction law.	–	Sweden: Downgrading the architect's skills.

Source: own work.

CONCLUSIONS

In both countries, the scope of work performed by the designer at the construction site depends on individual arrangements and also results from the provisions of the applicable law. The copyright states that a different architect cannot work on the project during any of its phases without the granted permission of the architect who is the author of the design. In Sweden, architects will most likely grant that possibility to a different architect upon the investor's request. An architect has a greater chance of continuing that design through all phases based on parameters such as recognition and reputation of the architect, a good relationship between the architect and the contracting authority, a lower price and securing with an appropriate contract/order.

This leads to the following conclusions:

1. Professional responsibility of the architect and the author's supervision that goes with it in Poland not only gives the architect personal responsibility but also allows them to maintain the quality and standards that guide their professional work. This enables the creation of architecture to be an interplay between "*firmitas* (construction system), *utilitas* (utility) and *venustas* (aesthetics)" (Cernaro, Fiandaca, Lione & Minutoli, 2023).
2. The lack of the architect's supervision in the execution of projects in Sweden can result in the creation of typical and homogeneous architecture, often resulting in inferior quality materials and details used.
3. The professional responsibility of the architect and the regulated author's supervision in Poland could cause an unjustified cost increase as one of the factors. This can occur when an architect primarily focuses on the vision without considering the consequences for functionality and maintenance.
4. The lack of the architect's supervision in the executive project in Sweden often results in lower construction costs due to shorter building duration, but it may also lead to the use of lower quality materials and less-than-ideal detailing solutions.
5. Investors in Sweden have the power to decide how many architects will work on different phases of a project and have the opportunity to provide input on the details. This power has been granted to the investor based on economic parameters, market conditions and acceptance of architects. In Poland, however, investors have a much lower level of influence over architects due to legal regulations.

Authors' contributions

Conceptualisation: D.W., K.W. and M.P.; methodology: K.W.; validation: D.W. and K.W.; formal analysis: K.W.; investigation: K.W.; resources: K.W.; data curation: K.W.; writing – original draft preparation: K.W.; writing: D.W. and K.W.; visualisation: K.W.; supervision: D.W., K.W. and M.P.; project administration: K.W.; funding acquisition: D.W. and K.W.

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

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PORÓWNANIE ODPOWIEDZIALNOŚCI ZAWODOWEJ ARCHITEKTA W POLSCE I SZWECJI

STRESZCZENIE

W Polsce tytuł architekta jest zawodem regulowanym i aby uzyskać uprawnienia budowlane w specjalności architektonicznej, należy spełnić wiele wymagań. Po drugiej stronie Bałtyku, w Szwecji, gdzie zawód architekta jest również zawodem regulowanym, odpowiedzialność zawodowa przedstawia się inaczej. Porównanie Polski i Szwecji pod kątem odpowiedzialności zawodowej architekta ma na celu analizę, w jaki sposób proces projektowania architektonicznego może wpływać na jakość architektury oraz relację architekta z inwestorem. Analizując te zależności, można zaobserwować tendencje w stylach architektonicznych i kosztach budowy. Porównanie tych dwóch krajów w temacie odpowiedzialności zawodowej polega na analizie trybu nadania tytułu architektonicznego i otrzymania wymaganego wykształcenia. Kolejnym elementem w porównaniu jest kwestia odpowiedzialności. W Polsce architekt ma odpowiedzialność cywilną, podczas gdy w Szwecji przeciwnie. Fakt, że na wszystkich etapach projektu w Polsce pracuje ten sam architekt, pozwala na lepszą realizację założeń projektantów – w przeciwieństwie do Szwecji, gdzie fazy projektu krążą między różnymi architektami, a twórca koncepcji ma ograniczoną kontrolę nad wynikiem końcowym, jeśli chodzi o rozwiązania, detale i materiały. Różnice te wpływają zatem na jakość architektury.

Słowa kluczowe: architektura, Polska, odpowiedzialność zawodowa, zawód regulowany, Szwecja

AN ANALYSIS OF THE SUPPRESSION OF A PAIR OF ODD AND EVEN TEMPERATURE FLUCTUATION IN AN AREA OCCUPIED BY A TWO-PHASE ONE-DIRECTIONAL PERIODICALLY LAYERED COMPOSITE

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ABSTRACT

The study concerns a heat conduction problem in a two-phase, one-directional periodically layered composite (commonly referred to as a laminate). The model is strictly related to considerations regarding continuous media and was introduced by Professor Czesław Woźniak. The basis for the study is a re-formulation of the heat conduction model for composites, referred to in the literature as “the extended tolerance heat conduction model”. The model equations consider coefficients responsible for the intensity of exponential and rotational suppression of boundary fluctuations of a temperature field in a limited area or in a half-space occupied by the composite. The study investigated the dependence of the suppression intensity of boundary fluctuations on the geometrical and material properties of the composite. Three special cases of pairs of interacting boundary fluctuations were analysed.

Keywords: effective heat conduction, periodic composite, boundary effect, extended tolerance model

INTRODUCTION

Composite materials, due to their insulating properties, are widely used to protect certain rooms from the harmful effects of thermal fields and resulting displacement fields. Thermal loads acting on composite materials cause fluctuations in the temperature field at the boundaries. This results in the formation of a so-called “near-boundary layer” (similar to a boundary layer in fluid mechanics) on both sides of a composite baffle, as if the ambient temperature automatically adjusts to the non-homogeneous structure of the composite. The boundary fluctuations that occur in this way are suppressed within the baffle during heat transport through the composite area. The movement of the boundary temperature impulse through the composite baffle is subject to two types of reactions: exponential suppression and rotational suppression (i.e., pulsations perpendicular to the baffle wall). The intensities of these two suppressions are functions of a quotient of conductivities $\kappa = k_{II}/k_I$ and a saturation of one of the components η . The periodic composites ensure the best suppression of disturbances in directions perpendicular to a periodicity direction.

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The aim of the paper is to attempt a description of the relationship between the suppression of fluctuation intensity in directions perpendicular to the periodicity direction and the internal structure of the composite. The results of the study on the boundary effect should contribute to designing composites with the best insulation properties. The boundary effect can be understood, in general, as the influence of boundary conditions on physical phenomena occurring in the composite. The analysis of this effect is strictly related to the fact that the equations of thermoelasticity contain components with a second spatial derivative. The analysis of the boundary effect in this study is restricted merely to heat conduction described by Fourier's conduction law. The extended tolerance model, applied here, has been described and used in many works (Kula, Mazewska & Wierzbicki, 2012; Kula, 2016; Kula, Wierzbicki, Witkowska-Dobrev & Wodzyński, 2018; Wierzbicki, Kula & Wodzyński, 2018a; Wierzbicki, Kula & Wodzyński, 2018b; Kula & Wodzyński, 2020; Wodzyński, Kula & Wierzbicki, 2018). The approach to the boundary effect phenomenon, described in this study, has also been applied in research works using methods similar to the tolerance averaging technique (Kula, 2015; Szlachetka & Wągrowa, 2011; Witkowska-Dobrev & Wągrowa, 2015).

Fundamentals of tolerance modelling, which were used to derive the equations used in the present study, have been presented in the monograph by Wierzbicki and Woźniak (2000). The mathematical theory of tolerance modelling was developed by Ostrowski (2017). To capture the boundary effect, the study made use of results obtained by Wierzbicki (2019) and Kula and Wierzbicki (2019).

DESCRIPTION OF THE MODEL OF THE PHENOMENON AND THE METHODS USED

For the sake of simplification, it was assumed that the area occupied by the composite was a cuboid (Fig. 1). The axis OY determines the direction of periodicity. The temperature field θ inside the area is evoked by two constant temperature values: inside and outside the room. Moreover, the temperature field does not depend on time and is a function of geometrical variables (y, z). In this model, it was also assumed that the heat flux vector was continuous in the direction perpendicular to interfaces between the components of the composite and that the components themselves were isotropic. Such conditions of heat conduction are mathematically expressed by a boundary problem for the parabolic equation of heat conduction:

$$\rho c \dot{\theta} - \nabla^T [K \nabla \theta] = 0, \quad (1)$$

where the symbols K , ρ and c represent respectively: heat conductivity matrix, mass density field and specific heat field.

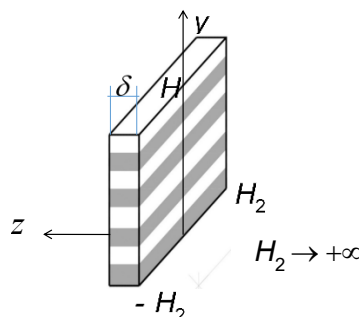


Fig. 1. Two-phase one-directional periodic composite

Source: own work.

Further considerations concern an analysis of the phenomenon of the transport of a pair of two interacting fluctuations, odd and even, through the composite. The Fourier's fluctuations under consideration are sums of products of Fourier's amplitudes a_1 and a_2 with related shape functions, also referred to as impulses. These temperature impulses are defined by the formulas (2) and formulas (13):

$$f_{EVEN}(v_1, y) = \begin{cases} -\frac{\lambda}{2}\alpha_1 - \frac{\lambda}{2}\alpha_1 \cos\left(\frac{2\pi v_1}{\lambda\eta_I}y + 2\pi v_1\right) & \text{for } -\lambda\eta_I \leq y \leq 0 \quad \alpha_1 = \frac{1}{\eta_I} \\ \frac{\lambda}{2}\alpha_2 + \frac{\lambda}{2}\alpha_2 \cos\left(\frac{2\pi v_1}{\lambda\eta_{II}}y - 2\pi v_1\right) & \text{for } 0 \leq y \leq \lambda\eta_{II} \quad \alpha_2 = \frac{1}{\eta_{II}} \end{cases} \quad (2)$$

$$f_{NP}(v_2, y) = \begin{cases} -\frac{\lambda}{2}\cos\left(\frac{(2v_2-1)\pi}{\lambda\eta_I}y + (2v_2-1)\pi\right) & \text{for } -\lambda\eta_I \leq y \leq 0 \\ -\frac{\lambda}{2}\cos\left(\frac{(2v_2-1)\pi}{\lambda\eta_{II}}y - (2v_2-1)\pi\right) & \text{for } 0 \leq y \leq \lambda\eta_{II} \end{cases}$$

The parameter v assumes positive integer values. A mean of each of the impulses within the individual cell must be equal to 0: $\langle f_{EVEN}(v_1, y) \rangle = \langle f_{ODD}(v_2, y) \rangle = 0$. It is also a criterion for determining the coefficients a_1 and a_2 .

The averaging operation, applied here, is defined by the formula:

$$\langle f \rangle = \frac{1}{l^I + l^{II}} \int_{-l^I}^{l^{II}} f(y) dy. \quad (3)$$

The amplitudes of the fluctuations can only be determined if the analysed pairs of impulses create an orthogonal Fourier's basis (i.e., a definite integral of the product of impulses within an area of a simple cell is equal to zero). The impulses (2) are mutually orthogonal, so there is no need to "orthogonalise" them. These impulses act as tolerance shape functions in the extended tolerance model used in this study to examine the transportation of fluctuations through a periodic composite. In this model, the equations of heat conduction have the form (Kula & Wodzyński, 2020):

$$\langle c \rangle \dot{u} - \nabla^T (\langle k \rangle \nabla u + \langle k \nabla^T \varphi^p \rangle a_p) = -\langle b \rangle, \quad (4)$$

$$\lambda^2 (A_c^{pq} \dot{a}_q - \nabla_z^T A_k^{pq} \nabla_z a_q) + 2\lambda s^{pq} \nabla_z a_q + \{k\}^{pq} a_q = (L_a^{\lambda}[u])^p$$

and are binding in materially homogeneous parts of the area Ω occupied by the composite, wherein:

$$\{k\}^{pq} = \langle \nabla_y^T \varphi^p k \nabla \varphi^q \rangle, \quad 2s^{pq} = \langle \nabla_y^T \varphi^p k \varphi^q \rangle - \langle \nabla^T \varphi^q k \varphi^p \rangle. \quad (5)$$

In Eq. (4)₂, next to the derivatives of the highest order, there are coefficients $A_c^{pq} \equiv \langle \varphi^p c \varphi^q \rangle$, $A_k^{pq} \equiv \langle \varphi^p k \varphi^q \rangle$. The expression $(L_a^{\lambda}[u])^p$ in the right side of Eq. (4)₂ includes all averaged expressions containing heat sources. In Eq. (4):

- u represents the average temperature field;
- a_p represents the Fourier's amplitudes;
- k represents the effective conductivity matrix;
- c represents the specific heat field;
- φ^p, φ^q represents the coefficients constituting an orthogonal Fourier's basis.

Furthermore, Eq. (4) contains a scale parameter equal to a quotient of a characteristic length λ of the repeatable cell to a characteristic length of the area occupied by the composite. The symbol ∇_y is a denotation of the gradient operator $\nabla \equiv [\partial_1, \partial_2, \partial_3]^T$ related to the directions of periodicity and the formula $\nabla \equiv \nabla_z + \nabla_y$ specifies a projection ∇_z of the gradient operator on directions perpendicular to the directions of periodicity. The summation convention holds. Eq. (4)₂ is called the ‘equation of boundary effect phenomenon’. For the pair of impulses given in formulas (2), the equation of boundary effect phenomenon assumes the form:

$$\frac{d^4 a}{dz^4} + \frac{1}{\lambda^2} \left(\frac{4d^2}{\gamma_1 \gamma_2} - \frac{\langle k \rangle_H}{\langle k \rangle} \left(\frac{c_1}{\gamma_1} + \frac{c_2}{\gamma_2} \right) \right) \frac{d^2 a}{dz^2} + \frac{1}{\lambda^4} \left(\frac{\langle k \rangle_H}{\langle k \rangle} \right)^2 \frac{c_1 c_2}{\gamma_1 \gamma_2} a = 0. \quad (6)$$

In this equation, a represents both the amplitude a_1 and a_2 . The individual coefficients are given as:

$$\begin{aligned} \gamma_1 &= \frac{\langle k f_{EVEN} f_{EVEN} \rangle}{\langle k \rangle}, \quad \gamma_2 = \frac{\langle k f_{ODD} f_{ODD} \rangle}{\langle k \rangle}, \\ c_1 &= \frac{\langle k \nabla f_{EVEN} \nabla f_{EVEN} \rangle}{\langle k \rangle}, \quad c_2 = \frac{\langle k \nabla f_{ODD} \nabla f_{ODD} \rangle}{\langle k \rangle}, \\ d &= \frac{\langle k f_{EVEN} \nabla f_{ODD} \rangle - \langle k \nabla f_{EVEN} f_{ODD} \rangle}{\langle k \rangle}, \end{aligned} \quad (7)$$

wherein $\langle k \rangle = \eta_I k^I + \eta_{II} k^{II}$. The characteristic equation for Eq. (6) is a biquadratic equation:

$$R^4 + \frac{1}{\lambda^2} \left(\frac{4d^2}{\gamma_1 \gamma_2} - \frac{\langle k \rangle_H}{\langle k \rangle} \left(\frac{c_1}{\gamma_1} + \frac{c_2}{\gamma_2} \right) \right) R^2 + \frac{1}{\lambda^4} \left(\frac{\langle k \rangle_H}{\langle k \rangle} \right)^2 \frac{c_1 \cdot c_2}{\gamma_1 \gamma_2} = 0, \quad (8)$$

which can be transformed into a quadratic characteristic equation by changing the variables $r = R^2$:

$$r^2 + \frac{1}{\lambda^2} \left(\frac{4d^2}{\gamma_1 \gamma_2} - \frac{\langle k \rangle_H}{\langle k \rangle} \left(\frac{c_1}{\gamma_1} + \frac{c_2}{\gamma_2} \right) \right) r + \frac{1}{\lambda^4} \left(\frac{\langle k \rangle_H}{\langle k \rangle} \right)^2 \frac{c_1 c_2}{\gamma_1 \gamma_2} = 0, \quad r = R^2, \quad (9)$$

where $\langle k \rangle_H = \frac{k^I k^{II}}{\eta_I k^{II} + \eta_{II} k^I}$. The discriminant of Eq. (9) is given as:

$$\Delta \equiv \frac{1}{\lambda^4} \left[\frac{4d^2}{\gamma_1 \gamma_2} - \frac{\langle k \rangle_H}{\langle k \rangle} \left(\frac{c_1}{\gamma_1} + \frac{c_2}{\gamma_2} \right) \right]^2 - 4 \cdot \frac{1}{\lambda^4} \left(\frac{\langle k \rangle_H}{\langle k \rangle} \right)^2 \frac{c_1 \cdot c_2}{\gamma_1 \gamma_2}. \quad (10)$$

The roots of the characteristic equation are four complex numbers r_1, r_2, r_3 and r_4 , for which the minimum absolute value of the real part ω_{exp} , as well as the minimum absolute value of the imaginary part ω_{rot} , are interpreted in this contribution as exponential intensity and rotational intensity respectively. The exponential intensity ω_{exp} depends on the thermal resistance exerted by the conductor and the velocity of suppression of the fluctuations. The rotational intensity ω_{rot} expresses the velocity of trigonometric fluctuations. Both of these intensities, created by the impulses (2), can be calculated using the following formulas:

– for $\Delta \geq 0$:

$$\omega = \sqrt{\frac{1}{2} \left\{ \frac{1}{\lambda^2} \frac{\langle k \rangle_H}{\langle k \rangle} \left[\left(\frac{c_1}{\gamma_1} + \frac{c_2}{\gamma_2} \right) - \frac{4d^2}{\gamma_1 \gamma_2} \right] + \sqrt{\Delta} \right\}}, \quad (11)$$

– for $\Delta < 0$:

$$\omega_{\text{exp}} = \frac{1}{2} \sqrt{\frac{1}{\lambda^2} \left(\frac{\langle k \rangle_H}{\langle k \rangle} \left(\frac{c_1}{\gamma_1} + \frac{c_2}{\gamma_2} \right) - \frac{4d^2}{\gamma_1 \gamma_2} \right) + \left[\frac{1}{\lambda^2} \left(\frac{4d^2}{\gamma_1 \gamma_2} - \frac{\langle k \rangle_H}{\langle k \rangle} \left(\frac{c_1}{\gamma_1} + \frac{c_2}{\gamma_2} \right) \right) \right]^2} - \Delta,$$

$$\omega_{\text{rot}} = \sqrt{\frac{-\Delta}{\frac{1}{\lambda^2} \left(\frac{\langle k \rangle_H}{\langle k \rangle} \left(\frac{c_1}{\gamma_1} + \frac{c_2}{\gamma_2} \right) - \frac{4d^2}{\gamma_1 \gamma_2} \right) + \left[\frac{1}{\lambda^2} \left(\frac{4d^2}{\gamma_1 \gamma_2} - \frac{\langle k \rangle_H}{\langle k \rangle} \left(\frac{c_1}{\gamma_1} + \frac{c_2}{\gamma_2} \right) \right) \right]^2}} - \Delta. \quad (12)$$

If the expression inside the square root in (11) is not negative, then (11) represents the exponential intensity and the rotational intensity is 0. However, if the expression inside the square root in (11) is negative, then (11) describes two conjugated imaginary numbers, with the positive one being the rotational intensity. The graphs below present the dependences of the exponential and rotational intensity on the parameters κ and η , where κ represents the quotient of conductivities of the components and η means a share of one of these components in the whole volume.

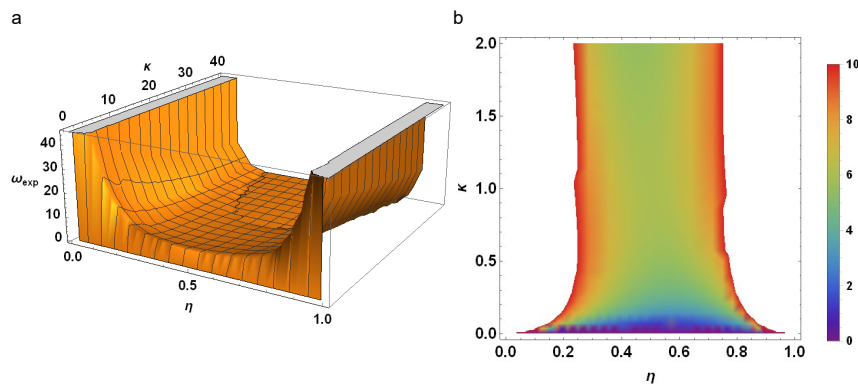


Fig. 2. Graphs for the pair of impulses (2): a – 3D graph of the exponential intensity; b – colour map for the exponential intensity within the range (0, 10)

Source: own work.

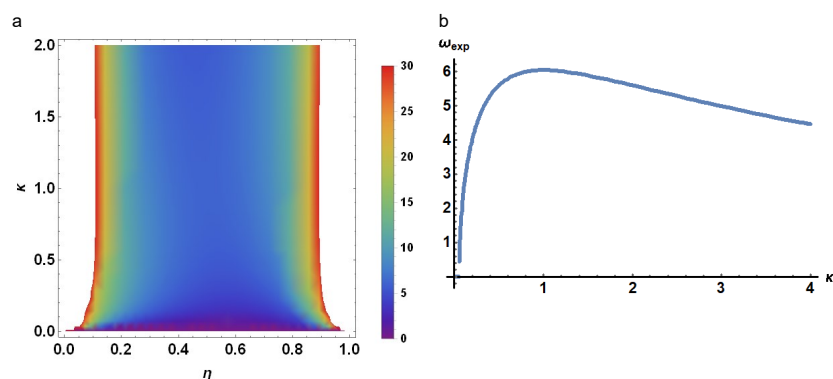


Fig. 3. Graphs for the pair of impulses (2): a – colour map for the exponential intensity within the range (0, 30); b – the exponential intensity for $\eta = 0.5$

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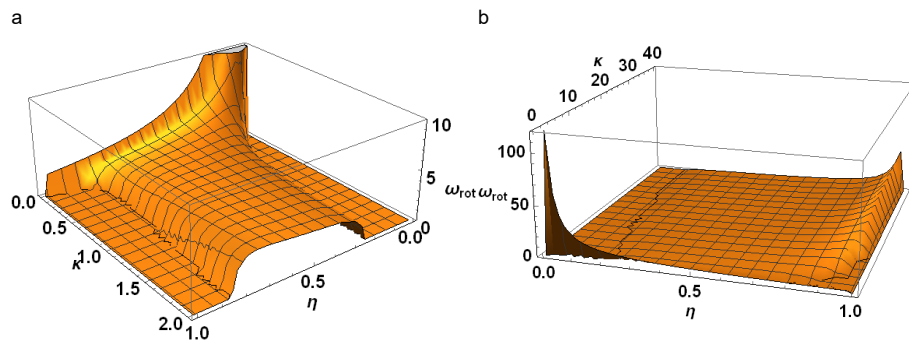


Fig. 4. 3D graphs of the rotational intensity for the pair of impulses (2): a – within the range (0, 10); b – within the range (0, 100) for κ varying from 0 to 40

Source: own work.

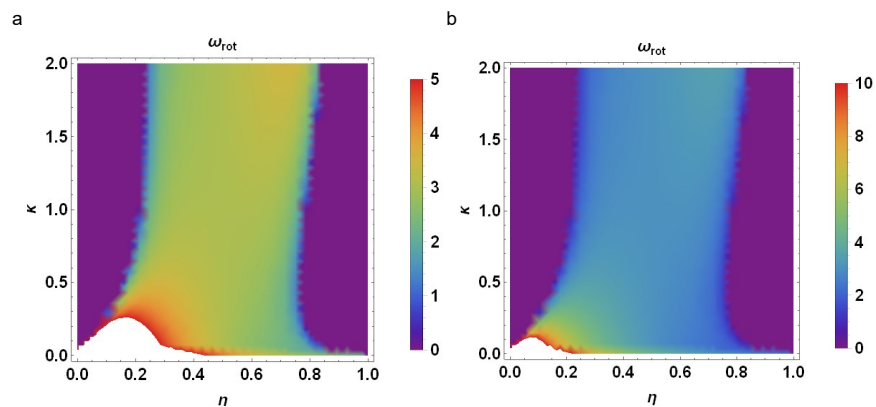


Fig. 5. Colour maps for the rotational intensity within the ranges: a – (0, 5); b – (0, 10)

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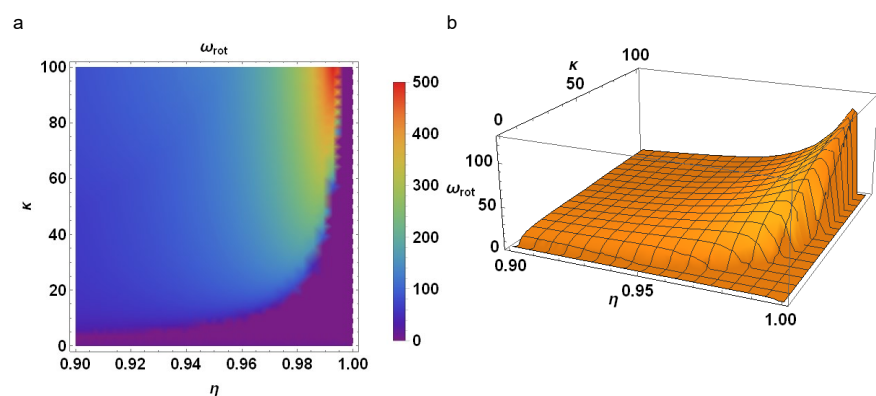


Fig. 6. Graphs of the rotational intensity for the pair of impulses (2) in the range accentuating a characteristic ridge

Source: own work.

In Figure 3b, the graph line is broken because the one-sided limit of this intensity is infinite in this point. A similar situation is for the function $y = \sqrt{x}$ in the point $x = 0$. A single point of indifferenciability corresponds to the condition $\Delta = 0$. The singularity occurs for $\kappa \approx 0.058$. The 3D graphs of the rotational and exponential intensities suggest that the highest suppression intensity occurs for an almost homogeneous structure of the baffle.

Interesting conclusions can be drawn after an analysis of suppression of the pair of impulses given by the formulas:

$$f_{EVEN}(v_1, y) = \begin{cases} -\frac{\lambda}{2}\alpha_1 - \frac{\lambda}{2}\alpha_1 \cos\left(\frac{2\pi v_1}{\lambda\eta_I}y + 2\pi v_1\right) & \text{for } -\lambda\eta_I \leq y \leq 0 \quad \alpha_1 = \frac{1}{\eta_I} \\ \frac{\lambda}{2}\alpha_2 + \frac{\lambda}{2}\alpha_2 \cos\left(\frac{2\pi v_1}{\lambda\eta_{II}}y - 2\pi v_1\right) & \text{for } 0 \leq y \leq \lambda\eta_{II} \quad \alpha_2 = \frac{1}{\eta_{II}} \end{cases} \quad (13)$$

$$f_{ODD}(v_1, y) = \begin{cases} f_{ODD}(v_2, y) + \beta f_{EVEN}(v_1, y) & \text{for } -\lambda\eta_I \leq y \leq 0 \quad \alpha_1 = \frac{1}{\eta_I} \\ f_{ODD}(v_2, y) + \beta f_{EVEN}(v_1, y) & \text{for } 0 \leq y \leq \lambda\eta_{II} \quad \alpha_2 = \frac{1}{\eta_{II}} \end{cases}.$$

The impulses $f_{EVEN}(v_1, y)$ and $f_{ODD}(v_2, y)$ have been previously defined. The equation of boundary effect is still fulfilled; the previously calculated coefficients γ_1 , c_1 and d remain unchanged. However, the coefficients γ_2 and c_2 change:

$$\gamma_2 = \frac{\langle k f_{ODD} f_{ODD} \rangle}{\langle k \rangle}, \quad c_2 = \frac{\langle k \nabla f_{ODD} \nabla f_{ODD} \rangle}{\langle k \rangle}. \quad (14)$$

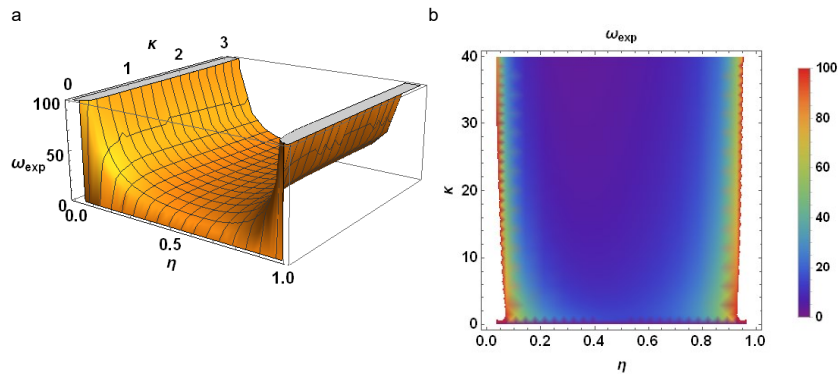


Fig. 7. Exponential intensity for the pair of impulses (13): a – 3D graph; b – colour map

Source: own work.

In a special case, when $\frac{c_1}{\gamma_1} = \frac{c_2}{\gamma_2}$ and $\beta \rightarrow \infty$, the roots of the characteristic equation are equal to:

$$R = \sqrt{\frac{4}{3} \cdot \frac{\langle k \rangle_H (\pi v_1)^2}{\langle k \rangle \lambda^4} \cdot \frac{\left[\frac{k_I}{\eta_I^3} + \frac{k_{II}}{\eta_{II}^3} \right]}{\left[\frac{k_I}{\eta_I} + \frac{k_{II}}{\eta_{II}} \right]}} \quad \vee \quad R = -\sqrt{\frac{4}{3} \cdot \frac{\langle k \rangle_H (\pi v_1)^2}{\langle k \rangle \lambda^4} \cdot \frac{\left[\frac{k_I}{\eta_I^3} + \frac{k_{II}}{\eta_{II}^3} \right]}{\left[\frac{k_I}{\eta_I} + \frac{k_{II}}{\eta_{II}} \right]}}. \quad (15)$$

The characteristic equation in this case has four real roots with equal modules and different signs. The positive part of these roots represents the desired exponential intensity. The rotational intensity is equal to 0.

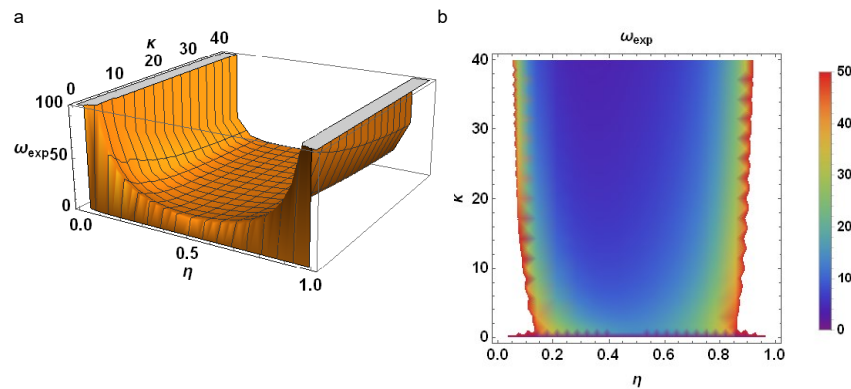


Fig. 8. Exponential intensity for the pair of impulses (13) for $\frac{c_1}{\gamma_1} = \frac{c_2}{\gamma_2}$ and $\beta \rightarrow \infty$: a – 3D graph; b – colour map

Source: own work.

SUMMARY AND CONCLUSIONS

In the study, appropriate formulas for two types of intensity in selected cases of fluctuation boundary loads were applied. Only the analysis of the suppression of pairs of fluctuations was conducted. The authors of this study are not familiar with the formal procedures for determining the critical points of the functions $\omega_{\text{exp}}(\kappa, \eta)$ and $\omega_{\text{rot}}(\kappa, \eta)$ in the case of pairs of fluctuations for which the set of two ordinary differential equations describing the boundary effect phenomenon transforms into a single fourth order equation, as it occurs in the cases being analysed in this study. Searching for the values of κ and η , for which the fluctuation suppression intensities reach extremely high values, is only possible in a numerical way and, therefore, it was the aim of the graphs obtained using computer programs and presented in this study. In order to better illustrate the results, colour maps for different parameter ranges (κ, η) were used in addition to the traditional graphs.

Based on a visual analysis of these graphs, one can state that the exponential suppression is the highest if η approaches 0 or infinity. Such a situation occurs when the baffle is almost homogeneous (the share of one of the components is close to 0), as well as in areas in the neighbourhood of the interface between the composite components. In the case of the rotational intensity for the first of the investigated pairs of fluctuations, the phenomenon is opposite to some extent – the rotational intensity is higher for the middle values of η . Certainly, the highest values of the rotational intensity occur in the neighbourhood of the point (0, 0). Moreover, if conductivities of the composite components are highly diversified ($\kappa > 20$), a distinct ridge of the rotational intensity exists within the range $\eta = (0.9, 1)$. This characteristic has not been illustrated or recognised in any of the previous studies on the subject. With regard to the argument κ , the maximum of the exponential suppression for both of the pairs of impulses exists within the range $\kappa = (0.4, 1)$.

The last of the discussed cases – the impulses (13) for $\beta \rightarrow \infty$ – can be of great importance in the mechanics, particularly in civil engineering: it suggests a set of fluctuations creating a relatively small threat of destruction of precise electronical devices placed in rooms whose walls are built of composite materials. In this case, the limit value of the rotational intensity is equal to 0, and the exponential suppression can be controlled by the saturation values of the composite components. A laboratory verification of the obtained results seems

to be possible only after transporting considerations onto the area of hyperbolic heat conduction or linear elasticity within the frames of wave analysis.

As a principal achievement of this study, it can be acknowledged that an identification of interacting fluctuations, both odd and even, was made. These fluctuations had unlimited amplitude and did not cause any damage to a device placed inside of a room with walls made of a composite material. The rotational intensity approached 0 after the limit transition of the parameter β to infinity. The exponential intensity was able to be controlled by a saturation parameter of one of the components of a two-phase composite.

Authors' contributions

Conceptualisation: E.W.; methodology: E.W., D.K. and Ł.W.; validation: D.K. and Ł.W.; formal analysis: D.K. and Ł.W.; investigation: E.W., D.K. and Ł.W.; resources: D.K. E.W.; writing – original draft preparation: Ł.W., writing – review and editing: Ł.W., D.K. and E.W.; visualisation: Ł.W., supervision: E.W. and D.K.

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

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ANALIZA TŁUMIENIA PARZYSTEJ I NIEPARZYSTEJ PARY FLUKTUACJI TEMPERATURY W OBSZARZE ZAJĘTYM PRZEZ DWUFAZOWY JEDNOKIERUNKOWO PERIODYCZNY KOMPOZYT WARSTWOWY

STRESZCZENIE

W pracy analizowane jest zagadnienie zjawiska efektu brzegowego dla dwufazowego kompozytu jednokierunkowo periodycznego i dla wybranych fluktuacji termicznych. Rozważania oparte na równoważnym przeformułowaniu parabolicznego równania przewodnictwa ciepła i rozszerzonym modelu tolerancyjnym prowadzą do wyłonienia optymalnej charakterystyki cech geometrycznych i materiałowych z uwagi na pożądane właściwości izolacyjne. Wprowadzono parametry intensywności tłumienia wykładniczego i rotacyjnego będące miernikami szybkości zanikania i oscylowania fluktuacji brzegowych jako mierniki intensywności zjawiska efektu brzegowego. Zbadano zależność intensywności tłumienia fluktuacji od właściwości geometrycznych i materiałowych przegrody. Przeanalizowano trzy szczególne przypadki par współpracujących fluktuacji.

Słowa kluczowe: efektywne przewodnictwo ciepła, kompozyt periodyczny, efekt brzegowy, rozszerzony model tolerancyjny

LANDFILL RECLAMATION USING THE EXAMPLE OF THE MUNICIPAL WASTE DISPOSAL PLANT IN PUŁAWY – A CASE STUDY

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ABSTRACT

Landfilling remains a dominant method of waste disposal worldwide, largely due to inadequate waste management frameworks, despite efforts to promote recycling and reuse. As populations and consumption levels grow, waste generation continues to increase, highlighting the need for effective waste management solutions. Landfills are sites where waste undergoes various physical, chemical and biological transformations, making the implementation of safety measures, leachate collection and gas recovery systems critical. This article presents a case study of the reclamation of the Puławy municipal landfill, which has been in operation since 1998. The reclamation process involved extensive steps such as forming the landfill body, securing the slopes, constructing a degassing layer, implementing a sealing layer and applying a cover layer. These measures were crucial in mitigating the negative environmental impact of the landfill, reducing harmful emissions and improving local groundwater quality. The results of the Puławy municipal landfill reclamation include reductions in leachate and gas emissions, improvements in air/groundwater quality and the transformation of the site into a green space that provides recreational opportunities for the community. This reclamation project serves as a model of responsible waste management and community involvement, demonstrating how degraded landfills can be transformed into valuable public resources. The article also discusses the broader implications of landfill reclamation, noting both the positive and negative aspects. Benefits include environmental protection, resource recovery, enhanced biodiversity and improved quality of life for local communities. However, challenges such as the long-term monitoring and maintenance of reclaimed sites and the financial costs associated with reclamation efforts are also considered. This study also emphasises the importance of landfill reclamation in the process of shaping and promoting environmental sustainability, as well as addressing modern waste management challenges.

Keywords: waste management, landfill, reclamation, sustainability

INTRODUCTION

Landfilling is a common method of waste disposal worldwide, and countries such as the United States, China and India are the largest producers of municipal solid waste (Sabour, Alam & Hatami, 2020; Zoungrana, Hasnine & Yuan, 2022; Wang et al., 2024). As the human population and consumption both grow, the amount of waste generated continues to increase, creating an urgent need for humanity to effectively manage the problem (Chen, Bodirsky, Krueger, Mishra & Popp, 2020; Shah, Srivastava, Mohanty & Varjani,

2021). Despite efforts to promote recycling and reuse of waste materials, landfilling remains a common practice due to inadequate waste management frameworks in many countries (Sabour et al., 2020; Osazee, 2021). Landfills act as ecological reactors where waste undergoes various transformations, highlighting the importance of critical factors such as landfill safety, leachate collection and gas recovery systems (Ilahi & Agnihotri, 2021; Nanda & Berruti, 2021; Mondal, Choudhury, Kundu, Dutta & Samanta, 2023). With the increasing challenges of environmental pollution and waste management, landfill remediation is becoming an indispensable part of today's society (Koda et al., 2021a; Koda et al., 2021b; Koda et al., 2023; Wen, Zhao, Guan & Zhang, 2023).

Modern society is increasingly aware of the need to protect the environment and ensure sustainability for future generations (Kumar & Agrawal, 2020; Rajadesingu, Deepankara, Dowlath, Karuppannan & Arunachalam, 2021). In this context, landfill reclamation is not only an integral part of waste management strategies, but also symbolises a commitment to environmental protection and concern for public health and community welfare (Zorpas, 2020; Khan, Anjum, Raza, Bazai & Ihtisham, 2022).

Landfill reclamation is a process that involves various techniques, such as sealing the landfill, improving drainage, stabilising waste and restoring natural ecosystems (Koda, Podlasek, Osiński, Markiewicz & Vaverková, 2021a; Koda et al., 2023; Wen et al., 2023). Successful remediation can turn formerly contaminated sites into valuable resources for local communities, providing new recreational opportunities, green spaces and contributing to improved air and groundwater quality (Reddy, Janga & Kumar, 2024). The example of a reclaimed landfill in the Municipality of Puławy demonstrates how responsible waste management and community engagement can transform problematic sites into valuable public spaces that serve both people and nature.

Landfill reclamation is the process of restoring land that has been used as a landfill to a useful or environmentally acceptable condition (Madadian, Haelssig & Pegg, 2020; Jakimiuk, 2022). Reclamation is carried out according to the schedule of landfill reclamation activities. The reclamation process is carried out in a way that protects the landfill from its harmful effects on surface and groundwater and air. The entire process should aim to integrate the landfill into the surrounding environment. Landfill reclamation has both positive and negative aspects. On the positive side, reclamation projects can significantly improve environmental quality (Nai et al., 2021) by reducing leachate and gas emissions, thereby protecting groundwater and air quality (Majewski, 2021; Kumari, Ahirwal & Maiti, 2022; Tan et al., 2022). These projects can transform run-down areas into green spaces that provide recreational opportunities and enhance the aesthetic value of the community (Artuso, Cossu, He & She, 2020; Koda et al., 2021b). In addition, reclaimed landfills can be repurposed for a variety of uses, including industrial, commercial or residential development, contributing to local economic growth (Ospanbayeva & Wang, 2020; Wenhong, Ridong & Jiayi, 2021). On the negative side, landfill reclamation can be costly and resource-intensive, requiring significant financial investment in site preparation, waste stabilisation and long-term monitoring (Titova, Shmandiy, Kharlamova, Rygas & Malovanyy, 2022; Sternik & Andrianova, 2023). The process can also present technical challenges, such as managing residual contamination and ensuring the stability of the reclaimed site (Majewski, 2021; Jakimiuk, 2022; Koda et al., 2023). There is also the risk of unforeseen environmental impacts, such as the re-release of contaminants during excavation and treatment. Despite these challenges, the long-term benefits of landfill reclamation often outweigh the drawbacks, making it an important strategy for sustainable waste management and environmental remediation.

This article highlights the importance of landfill reclamation in the context of today's environmental challenges and discusses key aspects of the process, its goals, methods and benefits to society and the environment. By exploring this topic through the example of a reclaimed landfill in the Municipality of Puławy, it is possible to explain why landfill reclamation is not only a necessity, but also an opportunity to create a more sustainable and environmentally friendly future.

MATERIAL AND METHODS

Landfill description

The facility is located on the premises of the municipal waste disposal plant (MWDP) in Puławy, at Dęblińska 96 (Fig. 1), approximately 6.7 km northwest of the centre of Puławy (GPS coordinates of the landfill: 51°28'02.0"N 21°56'10.0"E), along the National Road 801 (Warsaw–Otwock–Karczew–Wilga–Maciejowice).



Fig. 1. Landfill site location

Source: <https://www.geoportal.gov.pl>.

The landfill is surrounded on three sides by forests managed by the Puławy Forestry Commission. On the south-eastern side are the remaining installations and facilities of the MWDP (Fig. 2).

The landfill is an existing facility, built in 1996 and has been in operation since 1998. It has the characteristics of a sub-level landfill, consisting of two sub-quarries. The sub-quarries store the waste of the group separately:

- 17 – wastes from construction, renovation and demolition of buildings and roads;
- 19 – wastes from waste disposal and neutralisation facilities and wastewater treatment and water management;
- 20 – municipal solid waste.

The area of the landfill calculated along the outer contour of the crown is 27,685 m³, while the total area occupied by the landfill is 3.17 ha. The target maximum ordinate of the waste crown is 135 m above sea level, and the total geometric capacity of the landfill is about 0.3 million m³. In accordance with Article 103(2) of the Waste Act of 14 December 2012 (consolidated text Dz.U. 2023 poz. 1587), the landfill located on the premise MWDP in Puławy is a landfill for non-hazardous and inert waste.

The following materials have been used to prevent leachate from entering groundwater: (i) bent mate made of VOLCLAY type sodium bentonite in a propylene matrix (with the ability to self-seal in case of puncture), with a filtration coefficient of 10–11 m·s⁻¹; (ii) AGRU PEHD geomembrane.

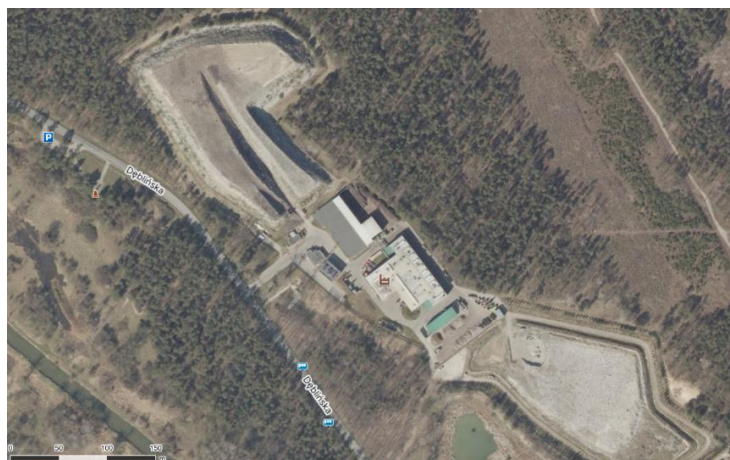


Fig. 2. Satellite aerial view of landfill in Puławy

Source: <https://mapy.cz>.

The geomembrane is protected from mechanical damage by a 40-centimetre-thick drainage protection layer with a 2/16 grain size. The drainage pipes are laid on a 4/8 gravel bed, which also protects the geomembrane from damage caused by the impact of coarser fractions of the filter layer (16/32). On top of the drainage protection layer, above the drainage pipes, a $400 \text{ g}\cdot\text{m}^{-2}$ geotextile is laid in 2,100-millimetre-wide strips.

Due to the profiling of the bottom of the basin with a bilateral slope to the north and south, there are two drainage basins. The theoretical daily leachate volume for average annual rainfall is 10.3 m^3 per day. The drainage network consists of four $\text{Ø}200 \text{ mm}$ pipelines laid along the longitudinal axis of the landfill. Leachate from the pipelines is collected in wells located outside the embankment of the landfill, four on the northern side of the basin and two on the southern side. From the wells, leachate is pumped to the pumping station and from there to a 162 m^3 leachate tank located on the southern slope of the landfill. Through the pumping station, the leachate from the tank is directed to the biofraction production process, which is carried out on the biofraction preparation line, a part of the MWDP plant. The unused amount of leachate is pumped out of the reservoir by a septic tank truck and directed to the wastewater treatment plant (WWTP). The groundwater monitoring system consists of five piezometers, while the landfill gas collection system is equipped with six degassing wells. A view of the landfill prior to reclamation is shown in Figure 3.



Fig. 3. Landfill in Puławy before reclamation – view from the south

Source: own work.

RESULTS

Activities related to the reclamation of the landfill

Pursuant to the regulations of the Waste Act of 14 December 2012, the Head of the Province issues a decision on the closure of a landfill and post-operational activities consisting of the reclamation of the site. In the case of the Municipality of Puławy, the decision was issued on 15 May 2019, clearly specifying the date of ending the dumping of waste and the stages of technical closure of the landfill. According to the above-mentioned decision, the process of the landfill closure and reclamation was divided into the following stages: (1) forming the body of the landfill, including the removal of depressions, delaminations and gaps by moving waste within the quarters and, if necessary, backfilling with materials or waste; (2) protection of the slopes and top from wind and water erosion; (3) construction of a degassing layer with a minimum thickness of 15 cm after compaction; (4) construction of a sealing layer of highly insulating materials, such as clay and clayey soils (a layer of 30 cm thickness in two stages of 15 cm each with compaction each time); (5) construction of a topsoil covering layer of 90–110 cm of material or waste; (6) seeding of grass mixture and planting of shrubs and maintenance treatments. The decision also includes a schedule of rehabilitation activities, as detailed in Table 1.

Table 1. Schedule of activities related to the reclamation of a part of the landfill

Scope of work	Completion deadline
Technical reclamation	
Cessation of waste acceptance	by 30 June 2019
Securing the landfill to prevent waste deposition	by 5 July 2019
Cleanup work around the landfill cell	by 15 July 2019
Clearing of fire roads, protective vegetation belts and cleaning and unclogging of perimeter ditches	by 15 July 2019
Grading work	by 31 July 2019
Inspection of degassing wells and securing materials for chimney extensions	by 31 July 2019
Protection of slopes and surfaces from wind and water erosion	by 31 July 2019
Installation of gas drainage	by 30 September 2019
Installation of sealing layer	by 15 November 2019
Biological reclamation	
Installation of covering layer with grass seeding	by 30 April 2023
Supplementary grass seeding	by 15 May 2023
Plantings	by 31 October 2023
Maintenance of plantings	by 30 April 2024

Despite these advanced construction activities, no construction permit is required for the closure and operation of the landfill. According to the Construction Law (consolidated text Dz.U. 2024 poz. 725, 834), construction work is defined as the building, installation, repair or demolition of a structure. Since landfill reclamation does not fall under any of the above categories, it does not require a separate construction permit. It is based solely on the decision of the provincial head.

Reclamation process of the landfill

The work on the already closed landfill was carried out according to the schedule established by the decision of the Head of the Lublin Province.

Protection of slopes and top against wind and water erosion

The process of securing the slopes and top of the landfill against wind erosion primarily consists of eliminating all cracks and natural water runoff from the landfill roof area. Additionally, any waste on the slopes that could interfere with the proper embankment of the slopes should be removed. Furthermore, the top of the landfill should be compacted using suitable equipment to achieve the highest possible compaction ratio.

Implementation of the gas drainage

The purpose of the gas drainage layer is to separate the waste from the reclamation layers, so it is necessary to compact the topsoil in such a way as to create a homogeneous, level layer (with no voids or holes) that provides an even base for the next layer. A gas drainage system of filter sand (river or mine sand) is laid on top of the landfill to remove landfill gases. Sand mixed with clay is allowed to increase the stability of the slope. It is assumed that the thickness of the degassing drainage layer after compaction will not be less than 15 cm. The execution and final result of this phase are shown in Figure 4. As part of this reclamation, a passive degassing system for the existing biogas extraction wells is planned. At this stage, the degassing column should be filled with aggregate to a level not lower than the designed ordinate of the sealing layer (i.e., at least 60 cm above the levelled drainage).



Fig. 4. Landfill during the construction of the layer separating the waste from the subsequent reclamation layers (left) and the final result (right) – view of the landfill entrance

Source: own work.

Implementation of the sealing layer

The sealing layer is designed to protect the landfill from the infiltration of rainwater and melted snow. The thickness of the sealing layer over the entire surface of the landfill embankment is 0.3 m. The sealing layer is made of a material with a high insulation coefficient, such as clayey or loamy soils.

Construction of a layer to protect the sealing lay

The topsoil layer is designed to protect the liner from erosion caused by excessive desiccation or rainwater runoff. If biological reclamation is not expected to occur quickly, this layer will also provide a place for plant growth and development.

Figure 5 illustrates a cross-section of the landfill, highlighting the current waste level in comparison to the designed final level. The diagram provides a detailed view of the various layers involved in the reclamation process. The cross-section through the layers of the reclaimed landfill depicted in the illustration showcases the original waste level and subsequent marked reclamation layers. At the top, there is a 0.15-metre erosion protection layer providing stability and protection. Below lies the sealing layer, aimed at preventing leachate from reaching the soil and groundwater. Next is the gas drainage system, designed to remove gases accumulated within the waste. Successive reclamation layers depict the gradual transformation of the landfill into an environmentally friendly area, enhancing its stability and minimising adverse impacts on the surroundings.

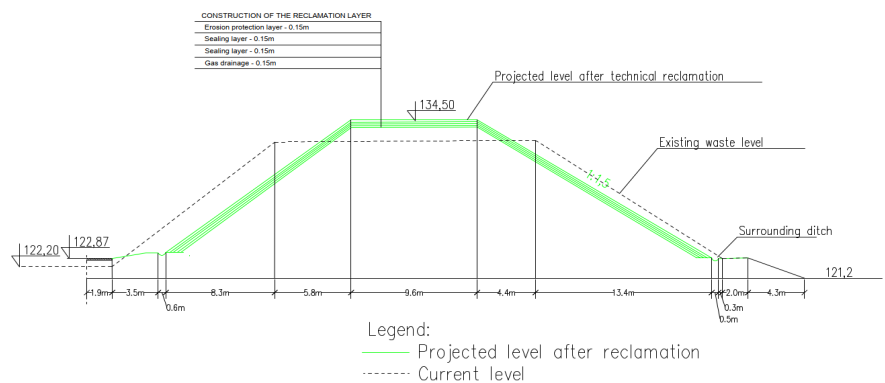


Fig. 5. Cross-section of the landfill showing the waste level and the designed level along with the reclamation layers

Source: own work.

Figure 6 shows a top view of the reclaimed landfill, illustrating the geometry and location of the degassing wells. Figures 7 and 8 depict the landfill in the Municipality of Puławy after recultivation, showcasing the transformation of the former landfill area into a sustainable green space.

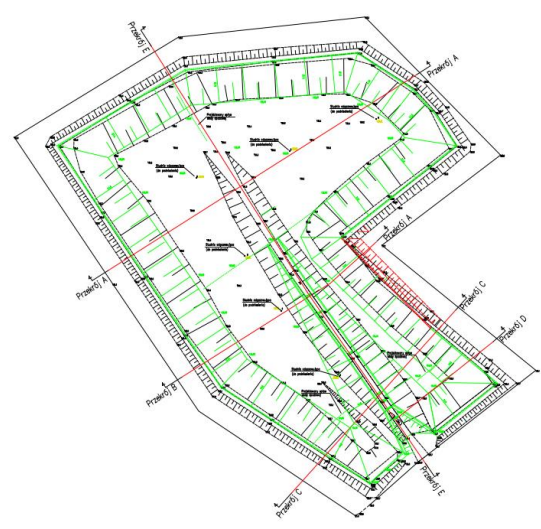


Fig. 6. Top view considering the geometry of the landfill in Puławy

Source: own work.



Fig. 7. View of the waste landfill in the Municipality of Puławy after recultivation – view from the east
Source: own work.



Fig. 8. View of the waste landfill in the Municipality of Puławy after recultivation – view from the south-eastern slope
Source: own work.

DISCUSSION

Landfill reclamation is an organised process aimed at mitigating the environmental impacts of waste disposal (Koda et al., 2021a; Koda et al., 2021b; Koda et al., 2023). Landfills, even when properly managed, can still pose a risk of contamination, making the reclamation of contaminated sites critical, as discussed in Liu et al. (2023). In countries such as India, where open dumping (non-sanitary landfills) is common, landfill reclamation (GHGs) using methods such as bio-mineralisation is critical to reduce greenhouse gas emissions, leachate pollution and land reclamation for sustainable reuse, as highlighted in Mohan and Joseph (2020). Overall, landfill reclamation is a multifaceted process that involves various strategies to minimise environmental degradation and maximise resource recovery.

The results of the reclamation of a waste landfill in the Municipality of Puławy indicate a significant impact of this process on the environment and the local community. First, recultivation activities significantly reduced the negative impact of the landfill on the environment, including contamination of ground and surface waters and the emission of harmful gases into the atmosphere. The technologies used, such as geomembranes and drainage systems, effectively protect the area against further degradation. Moreover, the reclamation of the Puławy landfill was carried out meticulously and according to schedule, ensuring comprehensive protection against wind and water erosion. Through the implementation of gas drainage and sealing layers, the site was effectively transformed into a sustainable green space that blends seamlessly into the surrounding environment.

To increase the broader applicability of this study, it is beneficial to compare the landfill reclamation project in Puławy with similar initiatives. Such comparisons can provide a broader understanding of the remediation of old landfills. For example, the reclamation of the Fresh Kills Landfill in New York transformed one of the world's largest landfills into a public park, highlighting the potential for large-scale ecological restoration (Klenosky, Snyder, Vogt & Campbell, 2017; Wilczkiewicz, 2017; Melosi, 2018). Similarly, the reclamation of the Tel Aviv Hiriya landfill in Israel shows how former landfills can be transformed into vibrant ecological parks and showcases innovative waste-to-energy technologies (Limor-Sagiv & Lissovsky, 2023; Limor-Sagiv et al., 2024). At the national level, the Radiowo landfill reclamation in Poland demonstrates effective methods for transforming landfills into green spaces that provide community benefits and improve environmental health (Koda et al., 2021b). Including these comparative examples not only broadens the context, but also illustrates different approaches and outcomes in landfill reclamation.

Reclamation has also contributed to the restoration of land degraded by landfill activities, which is particularly important in the context of urbanisation and the needs of local communities (Ospanbayeva & Wang, 2020; Kumari et al., 2022). Reclaimed land can be used for recreational purposes (Koda et al., 2021b), which improves the quality of life for residents and for agricultural or industrial purposes, which supports the local economy.

The reclamation process in Puławy is also an example of the effective recovery of raw materials from waste, which promotes the sustainable use of natural resources. Thanks to sorting and proper waste management, it was possible to recover valuable raw materials that can be reused in various sectors of the economy.

Landfill reclamation also has a positive impact on biodiversity (Vaverková et al., 2022). The restoration of natural ecosystems in landfill areas promotes the recovery of habitats for many plant and animal species, which is crucial for the preservation of biodiversity (Koda et al., 2021b; Winkler et al., 2021; Vaverková et al., 2022).

Another important aspect of reclamation is improving the image of the local community. Caring for the natural environment and the health of residents builds trust in the local government and strengthens the sense of community. Reclamation projects often involve local residents, which builds ecological awareness and promotes responsible attitudes toward environmental protection. Research in Indonesia has shown that reclamation projects in regions such as Bangkalan Regency have engaged coastal communities, including fishermen, in the management of reclaimed land, leading to increased community well-being and economic opportunities (Dewi & Turisno, 2020). In addition, effective reclamation programmes can create employment

opportunities, increase local economic activity and boost merchant income, ultimately contributing to the overall image and well-being of the community (Pambudi, Utomo, Soelarno & Takarina, 2023).

Landfill reclamation can have long-term economic benefits (Ospanbayeva & Wang, 2020; Yu et al., 2020; Titova et al., 2022). Although the initial costs associated with landfill reclamation are high, in the long run, it can lead to a reduction in landfill management costs and the treatment of environmental impacts, benefiting both the municipal budget and residents. The Puławy example shows that landfill reclamation is a process with multiple benefits, including environmental protection and improvement of the quality of life for the local community. The long-term effects of land reclamation contribute to sustainable development, which is crucial in the face of today's waste management and environmental challenges. Further research is needed to examine the extended long-term effects and global comparisons to improve their applicability and relevance in different contexts and other similar sites.

CONCLUSIONS

Landfill reclamation is an integral part of today's waste management strategies. In the face of growing environmental and waste management challenges, remediation offers not only solutions to environmental problems, but also opportunities to create a more sustainable future. The example of a landfill in the Municipality of Puławy shows that responsible waste management and community involvement can transform problematic sites into valuable resources that serve both people and nature.

Benefits of landfill reclamation:

1. Environmental protection: reclamation reduces the negative impacts of landfills on soil, water and air, helping to protect the natural environment and public health.
2. Land reclamation: restoring land to a condition usable by the local community can allow it to be used for recreational, agricultural or industrial purposes.
3. Resource recovery: the reclamation process can recover valuable materials from waste, contributing to the sustainable use of natural resources.
4. Biodiversity restoration: restoring natural ecosystems promotes the reestablishment of plant and animal habitats, helping to preserve biodiversity.
5. Improved community image: landfill reclamation can improve the image of the local community by demonstrating concern for the environment and the health of local residents.
6. Reduce long-term costs: although the cost of landfill reclamation can be high, it can be cost-effective in the long run by reducing the costs associated with landfill management and pollution-related health problems.

The example of the landfill in the Municipality of Puławy demonstrates the multifaceted benefits of landfill reclamation, from environmental protection and resource recovery to community enhancement and economic savings.

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Author's contributions

Conceptualisation: K.G. and M.D.V.; methodology: K.G.; validation: M.D.V.; formal analysis: K.G.; investigation: K.G.; resources: K.G.; data curation: K.G.; writing – original draft preparation: K.G. and M.D.V.; writing – review and editing: M.D.V.; visualisation: K.G.; supervision: M.D.V.

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

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REKULTYWACJA SKŁADOWISKA ODPADÓW NA PODSTAWIE GMINY MIASTO PUŁAWY – STUDIUM PRZYPADKU

STRESZCZENIE

Składowanie odpadów pozostaje dominującą metodą ich utylizacji na całym świecie, głównie z powodu nieodpowiedniej ramowej polityki zarządzania odpadami, pomimo wysiłków na rzecz promowania recyklingu i ponownego użycia. Wraz ze wzrostem populacji i poziomu konsumpcji rośnie ilość wytwarzanych odpadów, co podkreśla potrzebę skutecznych rozwiązań w zakresie gospodarki odpadami. Składowiska odpadów to miejsca, w których odpady ulegają różnym przemianom fizycznym, chemicznym i biologicznym, co sprawia, że wdrożenie środków bezpieczeństwa, zabezpieczanie odcieków i stosowanie systemów odzyskiwania gazu mają kluczowe znaczenie. W niniejszym artykule przedstawiono studium przypadku rekultywacji składowiska odpadów komunalnych w Puławach, eksploatowanego od 1998 roku. Proces rekultywacji obejmował rozległe etapy, takie jak: formowanie bryły składowiska, zabezpieczenie skarp, wykonanie warstwy odgazowującej, wykonanie warstwy uszczelniającej oraz nałożenie warstwy przykrywającej. Działania te miały kluczowe znaczenie dla złagodzenia negatywnego wpływu składowiska na środowisko przyrodnicze, ograniczenia szkodliwych emisji i poprawy jakości lokalnych wód gruntowych. Rezultaty rekultywacji składowiska w Puławach obejmują zmniejszenie emisji odcieków i gazów, poprawę jakości powietrza i wód gruntowych oraz przekształcenie terenu w zieloną przestrzeń, która zapewnia możliwości rekreacyjne dla społeczności. Projekt rekultywacji służy jako model odpowiedzialnego gospodarowania odpadami i zaangażowania społeczności, pokazując, w jaki sposób zdegradowane tereny można przekształcić w cenne zasoby publiczne. W artykule omówiono również szersze implikacje rekultywacji składowisk odpadów, zwracając uwagę zarówno na pozytywne, jak i negatywne aspekty. Korzyści obejmują ochronę środowiska przyrodniczego, odzyskiwanie zasobów, zwiększoną bioróżnorodność i poprawę jakości życia lokalnych społeczności. Do wyzwań należy zaliczyć długoterminowe monitorowanie i utrzymanie zrehabilitowanych terenów oraz koszty finansowe związane z wysiłkami rekultywacyjnymi. W tym badaniu podkreślono również znaczenie rekultywacji składowisk odpadów w procesie kształtowania i promowania zrównoważonego rozwoju, a także w rozwiązywaniu współczesnych wyzwań związanych z gospodarką odpadami.

Słowa kluczowe: gospodarowanie odpadami, składowisko odpadów, rekultywacja, zrównoważony rozwój

INTEGRATING BUILDING INFORMATION MODELLING (BIM) INTO CONSTRUCTION: INNOVATIONS, CHALLENGES, AND GLOBAL PERSPECTIVES

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ABSTRACT

The contemporary construction industry is undergoing transformative changes driven by pervasive digitalisation, with building information modelling (BIM) emerging as a pivotal innovation. This paper explores the imperative of incorporating BIM into every new construction project, emphasising its potential to enhance collaboration, streamline processes, and foster innovation. Through a comprehensive analysis of BIM's application in Poland and globally, the review of current literature assesses various software tools and compares BIM methodologies with traditional construction practices. The paper also identifies opportunities and challenges associated with integrating emerging technologies in the construction sector. The findings emphasise the necessity of adopting BIM to improve efficiency, reduce waste, and enhance project outcomes. BIM technology has undeniably become an elementary component of the process of creating and managing information about a construction project throughout its life cycle, used in architecture, engineering, and construction management.

Keywords: building information modelling, facility management, augmented reality, clash detection, Revit, Archicad

INTRODUCTION

Due to its distinctive characteristics and the intricate processes involved, the construction industry offers a significant opportunity for innovation and the advancement of digitalisation capabilities in production. Building information modelling (BIM) is the most rapidly expanding application of computer-aided design and construction management (PwC Advisory, 2020b). The apparent necessity for advancement in this direction is driven by the requirement to coordinate the multidiscipline construction projects that are integral to computer integrated manufacturing (CIM).

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The primary drivers of growth in the construction industry are multi-faceted, but economic factors undoubtedly play a central role. This can be attributed to the substantial contribution of the architecture, engineering and construction (AEC) services sector to GDP, which has steadily increased over the years, and the rising value of construction investments annually. It is also worth noting that each investment project involves many participants, from architects and engineers to skilled tradespeople and labourers. The construction industry is a significant source of employment, with thousands of new workers joining the workforce annually, contributing to the economic vitality of communities nationwide (PwC Advisory, 2020a; Alirezaei, Taghaddos, Ghorab, Tak & Alirezaei, 2022).

The MacLeamy curve demonstrates the correlation between cost and time in construction projects, contrasting traditional design with modern design utilising BIM (Fig. 1). The curve illustrates project costs increasing in proportion to time, then increasing exponentially at a certain point. As a project progresses, the costs associated with revisions and changes begin to exert a dominant influence, although initially, these costs are primarily associated with planning, design, and construction. This principle underscores the significance of early involvement in meticulous planning and design to circumvent costly alterations later in the project. In the initial stages of a construction project, the decisions made can considerably affect the cost and efficiency of the project.

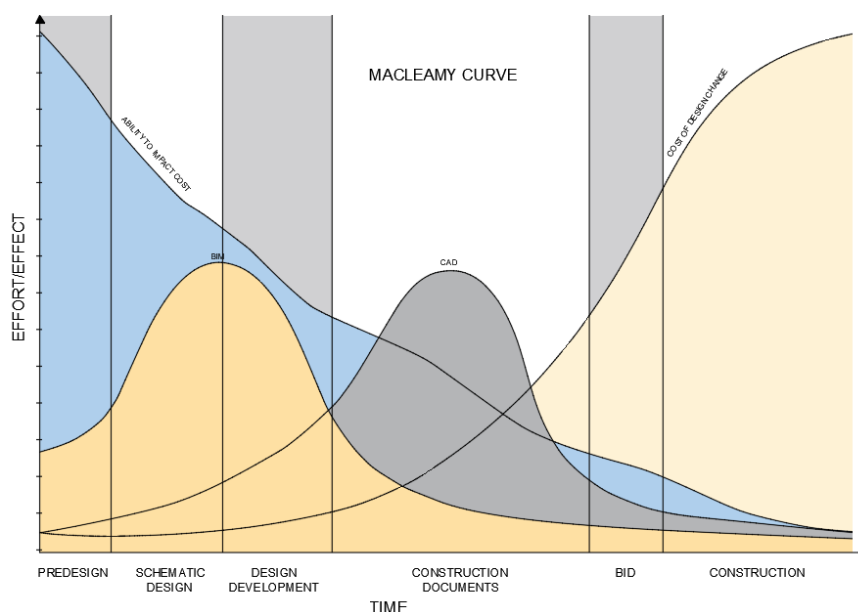


Fig. 1. MacLeamy curve

Source: Nguyen, Do, Le-Hoai, Nguyen and Pham (2022).

Another significant factor driving the expansion of this sector is the construction industry's relatively low productivity. This issue is closely linked to the reduced precision of manufacturing processes in comparison to other engineering sectors, a challenge rooted in the technical limitations of traditional on-site construction methods. These limitations stem from a lack of standardisation, limited repetition, and inefficiencies in design-build procedures. Shortcomings in process management, poor stakeholder coordination, and insufficient consideration of end-user requirements also further exacerbate these inefficiencies. The tightening of restrictive building regulations also poses a significant challenge. Moreover, the construction industry's inefficiency

is amplified by the substantial waste generated during the construction and demolition of buildings, positioning it among the highest carbon footprint sectors. In response, researchers and entrepreneurs are actively seeking more effective strategies for reusing waste and mitigating its environmental impact (PwC Advisory, 2020b).

In response to the issues outlined above, an increasing number of solutions are emerging in the marketplace to facilitate the processes involved in the design of buildings, the management of documentation, and the enhancement of collaboration between stakeholders in the investment process. Furthermore, stakeholders' utilisation of computer-aided construction process software is also increasing. The market leaders in structural design using BIM elements are as follows: notable software programs in this field include Autodesk Revit (and its other programs, such as Autodesk Civil), Graphisoft Archicad, and Vectorworks. The European market leaders in construction document management platforms have been Dalux, PlanRadar, and Thinkproject over the past few years. These tools are continuously evolving, making BIM more accessible to engineers and architects, as well as to contractors and construction managers.

The paper presents a comparative analysis and assessment of the risks and difficulties associated with using BIM tools in the architecture and construction sector. It analyses contemporary scientific literature, identifying opportunities and risks associated with implementing computerised tools. This is followed by examining the validity of introducing BIM tools into any construction project. The paper concludes with an evaluation of the advantages and disadvantages of using BIM and the results of using BIM in different stages of a construction task.

Evolution of building information modelling software

BIM is currently the predominant methodology for creating and updating information about a building throughout its lifecycle. Although the concept of BIM has existed since the 1970s, it was not until the advent of advanced computer capabilities in the early 2000s that this methodology truly evolved. Today, we can observe its significant influence across various domains of architecture and engineering.

The origins of BIM can be traced back to the 1970s and 1980s, aligning with the development of early computer-aided design (CAD) systems. These pioneering advancements marked the initial attempts to integrate various building data into a unified digital representation (Borkowski, 2023). By the late 20th century, BIM was widely accepted, encapsulating a comprehensive array of information within a computer-aided design environment.

BIM is a multi-faceted concept, with various activities and organisations adopting their standards and implementations, shaped by their projects' specific natures and scopes. As we entered the 21st century, advancements in technology allowed the concept of BIM to take on a more defined structure and direction. During this period, the development of standards and communication protocols became more understandable, leading to BIM's acceptance as a fundamental approach in the construction industry. However, its implementation and effectiveness largely depend on national standards and the results achieved within those frameworks.

Historically, the United Kingdom is regarded as the country that first introduced the widespread use of the BIM environment. The UK developed the BS 1192 standard (British Standards Institution [BSI], 2007), which forms the basis of the current ISO 19650 standard (International Organization for Standardization [ISO], 2023). The UK government's robust commitment to introducing BIM in the UK building sector has made it a global leader. It is a model for other countries to develop their BIM implementation strategies. Despite the continued existence of varying levels of BIM implementations globally, there is a discernible shift towards BIM becoming the foundation for resource-efficient development in architecture and construction. The direction of this shift is being shaped by practitioners who are implementing BIM at the highest levels of maturity (Borkowski, 2023).

Software compatible with building information modelling

The most prevalent pieces of software for BIM design are Autodesk Revit, Archicad by Graphisoft, and Vectorworks (Waas & Enjellina, 2022). These programs facilitate the design of building structures with a high degree of precision, which mitigates numerous complications during the construction phase and throughout the operational lifespan of the building structure.

The impetus for developing three-dimensional modelling programs was the CAD programs utilised for an extended period in the architectural and engineering industries. The software in question is primarily designed for the creation of two-dimensional drawings. In contrast to Revit or Archicad, it cannot store detailed data on building elements. The comprehensive capabilities of BIM-supporting programmes facilitate the creation of detailed models encompassing all aspects of construction while enabling interprofessional coordination between architects, builders and plant designers. These programs are focused on three-dimensional modelling, which means that changes made in one place are automatically updated throughout the project. This has the effect of eliminating errors due to outdated information. The existing industry foundation class (IFC) file extension allows all involved to collaborate on their respective design areas, reducing the duration of the design process, minimising the risk of errors and reducing costs in the construction process (Alfalah, Al-Sakkaf, Elshaboury & Abdelkader, 2021). The study examines the efficacy of document and task management platforms at construction sites.

Many platforms are emerging to facilitate the essential technical documentation processes during the design and construction phases. An illustrative example of such a solution is the platform proposed by Dalux, which has recently witnessed a notable increase in its market share in Poland and on a global scale. Dalux represents a comprehensive solution comprising modules and products, including the BIM Viewer – a highly expedient, cost-free three-dimensional model viewer that supports file formats such as BIM, IFC, DWG and PDF. The modules encompass Dalux Box, Dalux Field and Dalux FM.

The Dalux BOX module facilitates collaborative document editing and review among teams. The module facilitates the tendering, acceptance and verification of projects and the identification of discrepancies between versions. Furthermore, it facilitates convenient access to files at any time on computers and mobile devices (Khemlani, 2022). Dalux Field, conversely, is beneficial for the administration of tasks in situ. The tool is convenient and facilitates collaboration with subcontractors, defect reporting and reducing inspection and quality check times. Another distinctive solution is SiteWalk, a reality-capture function that challenges the conventional approach to visual documentation of on-site progress. The model, created in a few minutes, makes it possible to identify potential hazards, which can then be eliminated to maintain the safety of the work (Pereira De Sa & Gonzalez Alfaro, 2021; Khemlani, 2022). Dalux is one company that also offers solutions for property managers. To this end, additional modules have been developed: (i) BIM and documentation: a comprehensive collection of building information and service history; and (ii) Operations and maintenance: a repository for repetitive work orders and maintenance.

Application of building information modelling in the context of augmented reality

In the present era, there is a growing prevalence of discourse surrounding the exponential advancement of virtual reality. These considerations are most often related to video games. Virtual reality (VR) and augmented reality (AR) are being employed to integrate the tangible world with the capacity to conceptualise design solutions and rectify errors in real time. Utilising these tools permits the virtual navigation of a three-dimensional model of a building prior to the commencement of construction. This is advantageous for investors, general contractors, and prospective occupants of new residential and commercial premises. The application of this technology is becoming increasingly prevalent in construction-related tasks. The preliminary development of this technology highlights the necessity

of addressing the challenges that impede the comprehensive integration of these technologies in the context of modern construction sites.

The effective operation of VR and AR is contingent upon the availability of advanced equipment and high-speed, high-bandwidth networks, which is regarded as one of the principal challenges in this field. In the contemporary era, computer hardware is typically accessible; however, not all units possess the requisite computing power and, consequently, the accuracy to faithfully represent reality. To be fully convinced of the connection between the real and virtual worlds, sufficient accuracy needs to be achieved and ensure the image's smoothness. Further limitations relate to security and user privacy. As the technology develops, there are legitimate concerns about surveillance, espionage, privacy breaches, and data theft, particularly in the construction industry, where such sensitive data is desired by companies.

Notwithstanding the constraints outlined, virtual and augmented reality technologies demonstrate substantial potential for advancement within the construction industry. The principal limitation at this time is the cost of the equipment required to utilise VR and AR. Concurrently, concerning the developmental aspect, the objective should be to achieve greater accuracy and precision in the virtual world created with minimal hardware requirements. As this technology develops, it will also be necessary to establish appropriate regulations and standards regarding user protection issues.

Parametric design and fabrication in building information modelling

Software applications like Revit and Archicad offer distinct advantages over AutoCAD due to their incorporation of parametric tools like Dynamo and Grasshopper. These tools empower designers with the capability to create dynamic, data-driven models, providing efficient and systematic design processes. The incorporation further enhances the adaptability and versatility of these applications, making them indispensable for contemporary architectural and engineering practices.

The flexibility and adaptability of Dynamo and Grasshopper scripts make it easier to adjust designs in response to evolving project requirements and client feedback, promoting a more agile and responsive design process. This, in turn, leads to a more collaborative and iterative approach to design, which is particularly beneficial in complex, large-scale projects. Algorithms enhance processes in diverse technological fields, and their growing significance in defining architectural excellence is evident. Using computer-aided architectural modelling, including collaborative efforts such as BIM, has intensified the intrigue surrounding non-Euclidean geometric forms.

Moreover, BIM's importance in fabrication lies in its contribution to design flexibility, efficiency, and architectural precision. It empowers the creation of intricate, customised architectural forms while optimising material use and promoting sustainability. Integrating generative design and computational methods further enriches the design process by blending technical expertise with creative freedom (Stefańska & Dixit, 2020).

MATERIAL AND METHODS

This paper critically examines the risks and opportunities associated with utilising a BIM environment for interdisciplinary design and construction management during construction. These stages have been selected based on their potential for offering significant benefits and the availability of software on the market that is capable of supporting them. In light of the selected literature review findings, it was decided that investigating the necessity of utilising BIM for each construction project in the stages mentioned above would be beneficial. The potential applications of BIM at varying stages of its development were investigated. The selected literature comprises articles written between 2018 and 2023, thereby ensuring the inclusion of the latest capabilities and current technologies. The Scopus database was employed to identify articles that delineated contemporary issues about implementing BIM in construction practice. The terms 'building information

modelling’, ‘facility management’, and ‘augmented reality’ were used as search keywords in the Scopus database. A total of 319 articles meeting the specified criteria were identified by applying the above-mentioned boundaries. The subsequent analysis phase entailed selecting articles pertinent to utilising BIM in design and construction management.

As a consequence of this analysis, 20 articles were selected. Then, a compilation of different ways of using the BIM environment in the AEC industry was made, including a quantitative overview of the scientific articles (according to country of origin of the authors and publishers) on the BIM environment and the main thematic issues addressed in these articles. The results of the comparative analysis of the scientific literature are presented as a discussion of the advantages and disadvantages of using BIM in the construction sector and an exploration of potential future applications for this technology.

RESULTS AND FINDINGS

Incorporating BIM into the AEC industry has precipitated a profound transformation in how projects are designed, constructed, and managed. BIM is not merely a digital tool but a process that facilitates a collaborative environment where various stakeholders can contribute to a unified, comprehensive, and dynamic building or infrastructure project model. Such a model may encompass much information, including architectural details, structural elements, mechanical systems, and even construction schedules. The use of BIM facilitates improved coordination, reducing the probability of errors and conflicts occurring during the construction phase. A comprehensive, real-world view of the project by BIM facilitates improved decision-making, enhancing project outcomes and more efficient resource management throughout the facility lifecycle.

BIM is also being extended to facilities management (FM), where it is employed as a principal instrument for the upkeep and operation of buildings long after the construction phase has concluded. Implementing BIM provides facilities managers access to a comprehensive database that can be utilised for many purposes, including maintenance planning, space management, energy optimisation, and more. This integration of BIM with FM represents a shift towards more sustainable and efficient building management practices. Furthermore, combining BIM with new technologies such as the Internet of Things (IoT) and sensors enables real-time monitoring of building systems, thereby enhancing facilities’ operational efficiency and sustainability. Consequently, the role of BIM in the AEC industry is expanding, from improving the accuracy and efficiency of design and construction to supporting the ongoing management and optimisation of built environments.

BIM facilitates interprofessional collaboration and enhances the efficiency and quality of technical design and construction process supervision. Table 1 delineates the principal research areas currently being investigated through the utilisation of BIM in the AEC sector.

The analysis focused on the application of the BIM environment in the AEC sector summarises studies that have employed BIM in the AEC industry (Table 1). It also provides a list of specific articles and keywords that are directly related to the topic under study. This enabled a more comprehensive understanding of the issue to be achieved, and demonstrates the evolution of the BIM concept.

Table 2 provides supplementary information to that presented in Table 1, including the names of the journals in which the articles on the topic were published, and the number of articles published in each journal, the years in which they were written, and the average number of citations per article.

In selecting the analysis papers, an attempt was made to obtain a comprehensive overview of the changes and perceptions of BIM technology between 2018 and 2023, considering the various aspects of its implementation. At the same time, the data was kept up to date by selecting articles no older than five years.

Table 1. Studies focused on the application of the building information modelling environment in the architecture, engineering and construction industry

Reference	BIM research subject
Antón, Medjdoub, Shrahily and Moyano (2018), Nguyen et al. (2022), Lucchi (2023)	architectural details
Li and Lu (2018), Huang, Ninić and Zhang (2021), Mei et al. (2021), Chi, Juan and Lu (2022), Son and Han (2022), Kang, Kang, and Kim (2023), Liu, Zhang and Osmani (2023), Pu et al. (2023)	structural elements
Hwang, Zhao, and Yang (2019), Wang and Meng (2021), Katiyar and Kumar (2022), Kang et al. (2023)	construction schedule
Hosseini, Roelvink, Papadonikolaki, Edwards and Pärn (2018), Li and Lu (2018), Moreno, Olbina and Issa (2019), Wang and Meng (2021), Nour El-Din, Pereira, Poças Martins & Ramos (2022), Kang et al. (2023), Lucchi (2023)	facilities management
Maskuriy, Selamat, Ali, Maresova & Krejcar (2019), Alizadehsalehi, Hadavi, and Huang (2020), Xia, Liu, Efremochkina and Lin (2022), Lucchi (2023)	Internet of Things

Source: own work.

Table 2. Selected articles for analysis

Journal	Number of papers	Year	Citation average
Automation in Construction	3	2018 2020 2023	4–6
International Journal of Architectural Heritage	1	2018	2–4
Buildings	3	2022 2023	3–5
International Journal of Building Pathology and Adaptation	1	2018	2–3
Tunnelling and Underground Space Technology	1	2021	5–7
Journal of Construction Engineering and Management	2	2019 2023	5–7
KSCE Journal of Civil Engineering	1	2023	4–6
International Journal on Recent and Innovation Trends in Computing and Communication	1	2022	2–3
Applied Sciences	1	2019	3–5
Journal of Management in Engineering	2	2022 2021	4–6
Advances in Civil Engineering	1	2019	3–5
International Journal of Construction Management	1	2023	3–4
Journal of Computing in Civil Engineering	1	2023	4–6
Sustainable Cities and Society	1	2022	5–7

Source: own work.

Advantages of building information modelling

BIM facilitates enhanced investment process management, encompassing the planning stage and extending to the facility's design, implementation, and completion. This is made possible through implementing the common data environment (CDE) platform and preparing the facility management (FM) platform, which is used to manage an existing facility (Baldwin, 2019). BIM furnishes users with the requisite

tools to streamline the work of project participants. This approach to project management is conducive to the following aspects: site analysis, preliminary surveying, scheduling, energy analysis, sustainability assessment, three-dimensional coordination (e.g., clash detection and elimination), as-built documentation modelling, and FM platform planning. Furthermore, BIM facilitates improvements in contract management, task assignment and tracking, and project progress planning and reporting (Baldwin, 2019).

An investment process that is appropriately managed makes efficient use of all resources. BIM offers the potential to reduce the consumption of resources, including time, cost, and construction effort. Digital solutions that are both well-considered and effectively managed can facilitate the work of both client-side participants, and builders and designers (Wang et al., 2022). One potential application is the openBIM platform. This entails the establishment of an environment wherein each team member can operate at their optimal level, following their preferences and without the constraints imposed by other users. Implementing open standards and solutions enhances software interoperability and guarantees the precision of collaborative processes. Effective inter-industry coordination is a crucial aspect of BIM. This approach identifies potential conflicts before construction commences. Laser scanning techniques and 360-degree photography enable accurate building mapping, facilitating enhanced collaboration within the BIM environment, particularly in challenging, intricate, or linear objects (Stefańska, Markowski & Dixit, 2024) especially in the interdisciplinary Architecture, Engineering, and Construction sector (AEC). Such solutions permit expanding knowledge and facilitate the work of subcontractors, who frequently rely on two-dimensional documentation.

The utilisation of the CDE platform during the execution of a project facilitates the efficient management of subcontractors' work and the verification of tasks performed (PwC Advisory, 2020b). Fault forms, including photographic documentation and detailed descriptions, are assigned to the pertinent project participants responsible for a specific area. The information is catalogued appropriately, is readily understandable, and is accessible via a single phone or tablet application. The tools provided by the CDE platform serve to supplant the need for telephone or email communication and facilitate the reporting of work status tailored to the specific scope of work and project schedule. The platform facilitates various activities, including the management of tasks, health and safety inspections, and digital acceptance. Integrating a three-dimensional model, a comprehensive set of 360-degree photographs, and laser scanning technology enables a realistic representation of the site. It captures differences in documentation, thereby streamlining the creation of as-built documentation (Wang et al., 2022). The digital acceptance process allows for a more thorough inspection and quality control while reducing the time spent on excessive bureaucratic procedures.

Preparing an FM platform enhances facility management. It facilitates comprehension of and adherence to the client's requirements. The building transfer from one owner to another is contingent upon providing BIM and the capacity to utilise data accumulated from the project's inception. The FM platform facilitates data aggregation from manufacturers, subcontractors, and designers.

The three-dimensional model can also produce visual representations of the facility. By incorporating appropriate visual effects, the facility can be depicted at the proposed construction site as a standalone structure or in conjunction with surrounding buildings and landscaping. Such visualisations can be created to market the project effectively.

Incorporating contemporary technology into the construction industry represents a significant advancement in cost reduction and project acceleration. The overarching objective of BIM technology is to enhance the efficiency of routine operations, including the administration and documentation of projects, monitoring health and safety protocols, and facilitating inter-team communication. This aims to systematically organise information and analyse and learn lessons for future applications (Baldwin, 2019). The objective of BIM technology is to minimise and deconflict design flaws; that is, to reduce the incidence of human errors made during the preparation of design documentation and the implementation and management of the facility. Implementing more solutions and their regular use have increased employee and customer satisfaction.

BIM offers a multitude of benefits that can be leveraged to enhance various facets of construction projects. One of the principal advantages of BIM is its capacity to accurately represent intricate architectural elements, which is of particular significance in the context of historic building renovation projects (Antón et al., 2018). Furthermore, BIM facilitates the integration of disparate disciplines, thereby ensuring more consistent and precise project management (Nguyen et al., 2023). In the context of structural elements, BIM enables more effective visualisation, facilitating more informed design decisions and improving the final structures' quality (Chi et al., 2022). BIM also enables the management of construction schedules, reducing the number of revisions and accelerating projects through enhanced team coordination and resource optimisation (Hwang et al., 2019). In the context of facilities management, BIM facilitates the transfer of information from the construction phase to the operational phase, thereby enabling more effective monitoring of buildings and reducing maintenance costs (Hosseini et al., 2018). Furthermore, integrating BIM with IoT technology makes it possible to dynamically monitor construction processes and more efficiently manage resources (Alizadehsalehi et al., 2020).

Limitations and challenges during the introduction of BIM tools

Nevertheless, difficulties are frequently identified due to individuals' beliefs and apprehension about change. Standardisation and adherence to industry guidelines can prove challenging, and adapting the technology to existing processes can often encounter considerable internal resistance within many organisations. The effective management of data, the resolution of legal issues, and the reliance on particular service providers contribute further to the complexity and cost associated with implementing BIM.

The following aspects should be addressed in any form of digitisation:

- Lack of national and international standards. This is a significant challenge due to the lack of consistent guidelines across regions. This results in a dispersion of practices and data formats, complicating collaboration and hindering BIM implementation. There are, however, indications that progressive changes are being made to promote the development of BIM technology. Many countries, including China, the Czech Republic, and major technological giants like the UK and Germany, have started to create BIM standards, especially for infrastructure projects (Costin, Adibfar, Hu & Chen, 2018).
- Implementation of BIM is hindered by financial constraints, particularly the high initial investment required for software, hardware, and training. Furthermore, there are additional costs associated with ongoing software licensing, the necessity for robust hardware, staff training, integration with existing systems, data management and storage, difficulties in measuring return on investment (ROI), and additional costs related to risk management and legal and financial issues (Olawumi et al., 2018).
- Lack of qualified personnel. BIM is a nascent technology undergoing rapid development. Despite the numerous enhancements that have been made, it also presents new technological challenges for the construction industry. Technological advancement necessitates acquiring specialised skills, including software utilisation and data management proficiency. The process of sourcing and retaining experts can sometimes prove challenging, resulting in a discrepancy between the demand for and the availability of qualified personnel (Chan, Olawumi & Ho, 2019).
- Resistance to change. The apprehension surrounding the acquisition of novel technological skills impedes the rate of its integration. It can be challenging to persuade stakeholders of BIM's value, which can delay its broader implementation (Olawumi et al., 2018).
- The potential for privacy infringement, data security risks, and the possibility of technological obsolescence are significant concerns. Overcoming these challenges is essential to fully realising the potential of BIM in the construction industry.
- Software compatibility. In order for BIM to be effectively implemented, the various software applications must be compatible with one another. This can be a significant challenge, particularly in large-scale projects where multiple companies may utilise disparate BIM tools.

To address the challenge of the lack of consistent national and international standards for implementing BIM, it would be crucial to have a universal operational and technical framework that could be adapted across regions and for different projects. One potential solution is the development of a set of fundamental guidelines based on existing global standards, such as ISO 19650, which defines the principles of information management in BIM projects. Such a framework could be further enhanced by incorporating flexible components tailored to accommodate each country's distinctive legal, cultural, and technical requirements. A subsequent step would be to establish an international forum or working group comprising construction industry representatives from diverse geographical regions. The objective of this forum would be to monitor progress and develop standards by global trends in technology and construction practices. Furthermore, standardisation could encompass the harmonisation of data formats and software interoperability, which would considerably facilitate international collaboration and enable the full realisation of the potential of BIM in large-scale projects.

Numerous organisations have sought to leverage the experiences of other entities that have successfully deployed the technology to mitigate resistance to implementing BIM and to foster a culture of innovation. One illustrative example is the Crossrail project in the UK, which has become a model for BIM integration in infrastructure (Szarata, 2022). In addition to providing staff training, the project management team also established dedicated collaboration platforms to facilitate convenient access to project data for all stakeholders. The key to success was the gradual introduction of technology, which permitted teams to become accustomed to the new tools and processes. Similarly, in the Oslo Opera House project, the implementation of BIM was facilitated by educational initiatives and the involvement of technology leaders, which helped to overcome initial scepticism and resistance to change (Sauge, 2019). These examples illustrate that involving employees in the initial stages of technology implementation and providing the requisite tools and training to facilitate their adaptation to the novel working environment are pivotal to success.

RECOMMENDATIONS

To successfully implement BIM technology, it is essential to have clear, practical recommendations in place to overcome the challenges that have been identified. One potential solution is to establish and implement consistent national and international standards for BIM. Such a system would facilitate uniform cooperation between companies from disparate regions and facilitate data exchange. It is incumbent upon governments and industry organisations to provide active support for this process, including creating legislation promoting the use of BIM and allocating funding for training and technology investments. Providing tax incentives or subsidies for the early implementation of BIM could also provide further motivation for companies to overcome the financial barriers associated with the high initial costs involved.

One potential avenue for advancement is the implementation of comprehensive BIM training programs for both existing employees and students in construction and engineering. This would facilitate the widespread adoption of the technology by addressing the current skills gap. Concurrently, regarding software compatibility, the industry should develop open data formats (such as industry foundation classes), which would facilitate the integration of disparate BIM tools into complex projects. For instance, forming industry consortia to collaborate on developing interoperability standards between disparate software tools could potentially mitigate the challenges associated with software diversity.

To mitigate resistance to change, it is imperative to engage individuals at the outset of any BIM implementation and educate them on the advantages of the technology. Implementing change management strategies to overcome resistance to new developments and accelerate the adaptation process would be prudent. Moreover, in response to concerns about privacy and data security, it is imperative to implement robust data protection measures that align with the highest industry standards to enhance confidence in BIM technology.

It is worth considering cost-effective and strategic approaches to enable smaller firms to implement BIM incrementally and overcome financial barriers. One is a subscription model for BIM software, which reduces the one-off cost of purchasing a licence, allowing firms to spread the expense over time. Companies can also take advantage of free or cheaper versions of open-source software that offer basic BIM functionality, which can be a first step towards digitalisation. Another solution could be to gradually implement BIM technology in selected pilot projects, allowing firms to gain experience and assess the return on investment (ROI) before a full implementation. It is also worth considering working with third-party BIM service providers, allowing smaller firms to benefit from experts and technology without bearing the full cost of purchasing software and employing skilled staff.

DISCUSSION

The construction sector is experiencing sustained growth, which has resulted in an increased demand for integrating BIM into contemporary projects. BIM enables the simultaneous creation and management of virtual models. Such integration offers a multitude of advantages, including data aggregation, dissemination, and incorporation despite several constraints throughout the project life cycle.

A comprehensive analysis of the advantages and disadvantages of BIM was conducted through an extensive examination of 20 selected articles from the Scopus database, published between 2018 and 2023. The selected scientific articles were analysed according to the following topics: the subject areas under consideration are architectural details, structural elements, construction schedules, facilities management, and the Internet of Things.

The architectural details theme was the subject of analysis in three articles. The primary benefit of BIM, as posited by Antón et al. (2018), is the capacity to precisely model and document intricate architectural components, particularly in historical edifices. The creation of three-dimensional models semi-automatically is a possibility afforded by BIM, which significantly increases accuracy and reduces the risk of errors when reconstructing architectural details. Furthermore, the technology facilitates the integration of disparate engineering and architectural disciplines, thereby ensuring more consistent and precise management of restoration projects – a crucial aspect in preserving the authenticity of heritage buildings (Nguyen et al., 2022).

It should be noted, however, that BIM also has certain limitations. While the semi-automated modelling process increases precision, it is also time-consuming and requires advanced technical knowledge, which can be a barrier for some users (Antón et al., 2018). Moreover, implementing BIM in architectural detailing frequently entails considerable costs and the necessity for substantial financial and human resources, particularly in regions with limited access to technology (Nguyen et al., 2022). Moreover, the utilisation of digital twins in the automation of the building sector necessitates the continuous monitoring and management of buildings, which in turn requires the input of vast quantities of data and the deployment of sophisticated algorithms. This can prove challenging to implement in practice. Integrating these technologies with existing systems can be complex and costly (Lucchi, 2023).

The analysis was conducted on eight articles in the context of structural elements. Huang et al. (2021) emphasise the advantages of integrating BIM with machine learning and computer vision techniques in underground construction. This integration improves precision in planning and monitoring structural elements, which is crucial in environments where errors are likely to occur. In contrast, Pu et al. (2023) emphasise the importance of faster updating of BIM models in railway stations, which facilitates efficient management and maintenance of structural elements in dynamic environments while optimising interruptions. In their 2023 article, Son and Han present a method for automatically planning three-dimensional scans of prefabricated building components using BIM. This makes it possible to precisely adjust structural components on site, thereby reducing the risk of errors and improving assembly quality. Liu et al. (2023) posit

that BIM is a crucial tool for sustainable cultural heritage management, as it facilitates precise documentation and analysis of the condition of historic structural elements, thereby supporting their maintenance and preservation over time. Chi et al. (2022) observed that BIM facilitates enhanced visualisation and comprehension of the structural characteristics of buildings, thereby fostering more judicious design choices and superior-quality final structures.

Conversely, as Li and Lu (2018) demonstrated, incorporating geometric models with site imagery and GIS-supported BIM facilitates the precise representation and analysis of structural elements on site, enhancing management and decision-making processes.

The authors identify several potential limitations of BIM technology that could restrict its efficacy despite its numerous advantages in structural management. Huang et al. (2021) observed that integrating data from disparate sources and the scalability of BIM models present significant challenges in underground construction. This can result in inaccuracies in the representation and monitoring of structural elements in challenging underground environments. Similarly, Pu et al. (2023) indicate that a dearth of data can result in incomplete or inconsistent information regarding structural elements. This renders updating BIM models time-consuming and inaccurate, resulting in delays in infrastructure management and maintenance. Son and Han (2023) suggest that creating optimal three-dimensional scanning plans for prefabricated building components can be challenging due to the diversity of technical parameters and the intricate nature of BIM models. Such issues can lead to inaccuracies in mapping structural components, which may result in reduced assembly quality. Liu et al. (2023) posit that implementing BIM in the context of sustainable heritage management may present certain challenges. This is due to the absence of established standards and difficulties in integrating historical data with contemporary BIM models. These challenges can result in inaccurate documentation and analysis of structural elements in historic buildings. As Chi et al. (2022) observe, the implementation of BIM can present certain challenges, particularly in the context of structural elements. Inappropriate utilisation of the technology has the potential to result in design errors or difficulties in interpreting models. In 2018, Li and Lu demonstrated that the accurate mapping and management of structural elements can be challenging due to limitations in input accuracy and compatibility issues between different systems. A long-term study by Kang et al. (2023) indicates that the advancement of BIM is constrained by resistance to change in established work practices within the construction industry. The absence of standardisation and the challenges associated with adapting the technology can give rise to complications in the management of construction elements, ultimately leading to a detrimental impact on the efficiency of construction processes. In turn, Mei et al. (2022) highlight the challenges associated with formwork planning using BIM, particularly in the context of the potential reuse of structural elements. The absence of accurate data or its inadequacy can result in inefficient planning and elevated material costs.

In examining the subject of the construction schedule, four articles were subjected to analysis. BIM has several advantages and disadvantages in construction schedule management that can impede its effectiveness. First and foremost, integrating BIM with IoT technology enables the automatic monitoring of the construction progress of precast concrete structures. This markedly accelerates the monitoring process and mitigates delays by furnishing precise data on the construction status. As Katiyar and Kumar (2022) have observed, this facilitates more effective construction schedule planning. However, they also note that integrating BIM with IoT requires advanced technical expertise, potentially leading to system implementation delays.

Furthermore, BIM significantly reduces the necessity for revisions (rework) in construction projects, thereby reducing the project's overall duration. Hwang et al. (2019) posit that enhanced team communication and coordination can positively impact construction scheduling. Nevertheless, preliminary delays may be attributed to constraints such as the need for staff training and resistance to the comprehensive implementation of BIM (Hwang et al. 2019). Furthermore, Wang and Meng (2021) indicated in their paper that BIM facilitates knowledge management in construction projects, thereby enhancing the ability to plan and respond to change.

It is, however, important to reiterate that a lack of staff comprehension and acceptance of BIM can impede the implementation of the technology and adversely affect schedules (Wang et al. 2022). In Korea, a construction engineering study by Kang et al. (2023) demonstrated that BIM enhances the efficiency of the construction schedule by mitigating the risk of errors and delays and by facilitating the more effective planning and optimisation of resources, thereby accelerating project delivery. Furthermore, they indicate that issues surrounding the integration of BIM can result in elevated costs and delays.

The subject of facilities management (FM) was examined through seven articles. Hosseini et al. (2018) emphasise that enhancing information management and optimising data transfer from the construction phase to the facility operation represents a significant advantage of BIM. This enables managers to monitor and maintain buildings in a more effective manner, which in turn results in reduced costs and improved efficiency. Moreno et al. (2019) observe that BIM facilitates enhanced coordination between project teams and facility managers, streamlining change management and ensuring access to accurate data throughout the building lifecycle. Another advantage of BIM is its capacity to integrate with digital twin technologies. This can assist facilities management in more precisely monitoring the condition of buildings and predicting maintenance requirements. Nour El-Din et al. (2022) demonstrate that such integration results in cost and resource savings. Wang and Meng (2021) highlight the potential of BIM to facilitate knowledge management, which is crucial for effective building maintenance and lifecycle management.

Nevertheless, certain issues in FM necessitate the implementation of BIM. Hosseini et al. (2018) highlight the challenges associated with standardising processes and information requirements, noting that facility managers often lack the requisite knowledge and skills, which impedes realising BIM's full potential. Moreno et al. (2019) indicate that traditional construction companies encounter challenges adapting to new technologies and absorbing the high upfront costs associated with implementing a BIM process. Moreover, they underscore the dearth of interoperability between FM tools and disparate BIM systems.

As Nour El-Din et al. (2022) observed, deploying digital twins necessitates a sophisticated IT infrastructure and specific expertise, which may prove challenging for numerous organisations. Wang and Meng (2021) posit that contemporary IT systems are necessary for the management of BIM data, which can present challenges, particularly in the context of older buildings. Lucchi (2023) notes that implementing BIM in the heritage industry can present unique challenges due to the distinctive characteristics of these buildings and the intricate nature of the conservation processes involved.

The subject of the Internet of Things was examined in four articles. Integrating BIM and the IoT provides the potential for enhanced monitoring and management of construction and operational processes within buildings. As Alizadehsalehi et al. (2020) observed, integrating real-time data gathered by IoT sensors into the BIM model facilitates more effective decision-making and enables dynamic model updates. Maskuriy et al. (2019) observed that the real-time monitoring capabilities afforded by integrating IoT and BIM facilitate the intelligent management of construction resources and enhanced operational efficiency. In the context of smart city design, Xia et al. (2022) posit that integrating BIM and IoT facilitates the dynamic monitoring and optimisation of urban operations by utilising real-time data fed into digital twins. In contrast, Lucchi (2002) asserts that integrating IoT and BIM in the context of building heritage facilitates precise monitoring of the condition of historic structures, thereby enabling the automation and safeguarding of these assets.

While there are numerous advantages to integrating BIM and the IoT, Alizadehsalehi et al. (2020) are aware that there are also some obstacles to be overcome. The process is complex and necessitates the presence of an advanced technological infrastructure and relevant expertise, which can impede the comprehensive integration of this technology within the construction industry. Moreover, as Maskuriy et al. (2019) discovered, the construction industry is not yet sufficiently prepared for the widespread implementation of these technologies. The potential issues of data security and the absence of established standards may impede the interoperability of BIM and IoT systems. Moreover, Xia et al. (2022) highlight the challenge of integrating

disparate technologies, which necessitates a unified approach and a robust technological infrastructure. Furthermore, managing the vast quantities of data generated by the IoT may present challenges, potentially impeding its analysis and utilisation.

BIM plays a pivotal role in the optimisation of costs, as well as the generation of comprehensive cost estimates at various stages of a construction project. BIM facilitates the generation of precise cost predictions based on accurate data about materials, human resources, and work schedules. BIM facilitates the generation of cost estimates in real time, enabling dynamic budget monitoring and rapid response to project changes. BIM integrates various information sources, accurately tracking costs associated with each phase of a building's lifecycle, from design through construction to FM. It is also noteworthy that the technology permits the examination of disparate design alternatives in terms of their cost implications, thereby facilitating the decision-making process for investors and contractors. As Hosseini et al. (2018) observe, the automatic updating of BIM models ensures that changes to cost estimates are immediately visible, reducing the risk of budget overruns. The process of creating cost estimates using BIM does, however, require advanced technical skills and appropriate software, which can act as a barrier for smaller construction companies that do not have the necessary technological infrastructure. It is, therefore, essential to explore further how BIM can be used to improve costing processes and identify the technological challenges that must be overcome to implement this technology fully in construction cost management.

CONCLUSIONS

Notwithstanding the many impediments and constraints, BIM facilitates data aggregation, dissemination and integration throughout the project life cycle. The capacity of BIM processes to facilitate visualisation and interoperability is vital within the construction industry. The inherent uncertainty of construction projects and the difficulties associated with locating existing infrastructure are challenges that are not immediately apparent at the project's outset. Applying contemporary technology and utilising a BIM environment can effectively mitigate potential conflicts.

BIM is increasingly regarded as the future of construction, with the potential to deliver substantial benefits, including enhanced efficiency, superior project quality, and reduced operational costs. It is incumbent upon construction companies and contractors to carefully consider these limitations and adapt their approach to any BIM implementation in a manner that is sensitive to the specifics of the project in question and the available resources and technology.

BIM technology is most effective during the design stage. The maximum value of the work input, and therefore the cost, is reached at the documentation stage of a construction project, at which point, CAD programs are fully utilised. In contrast, at the construction stage, the value of the work input is diminished. Consequently, the total commitment required in the construction process with this tool is less than that required by traditional computer-based methods.

It should be noted that the interpretation of the results may be limited by using a single database, namely Scopus. Not all articles on BIM may be included. Furthermore, the restriction on the publication period of the articles analysed, which covers the years 2018–2023, represents an additional impediment to obtaining comprehensive results. It should be noted that the BIM topics extend beyond the present academic period and do not include papers currently prepared for publication. Moreover, the narrowing of the research scope using specific keywords, such as 'building information modelling', 'facility management' and 'augmented reality', limited the scope of articles to a mere 319 results, of which only 20 were selected for further analysis, reducing the fullness of the observations. These factors may restrict the scope of the conclusions that can be drawn and potentially impact the accuracy and generalisability of the results.

The study yielded several pivotal findings. These include a comprehensive grasp of the perils and complexities of deploying BIM in construction, encompassing its advantages and disadvantages. The study illuminates strategies for surmounting BIM's constraints and challenges to the construction sector. The analysis offered valuable insights for the construction industry, demonstrating how innovative programs can transform and optimise the construction process and assist in avoiding potential risks.

Authors' contributions

Conceptualisation: A.S. and M.Ku.; methodology: A.S. and M.Ku.; validation: M.Ko., M.N. and K.K.; formal analysis: M.Ko. and K.K.; investigation: M.Ku., M.N., Z.J., M.Ko., K.K., K.R., E.G., M.S. and E.F-P.; resources: M.Ku., M.Ko., M.N. and K.K.; data curation: M.Ku., M.N., M.Ko. and K.K.; writing – original draft preparation: M.N., Z.J., M.Ko., K.K., K.R., E.G., M.S. and E.F-P.; writing – review and editing: M.Ku., M.Ko., K.K. and A.S.; visualisation: M.Ku., M.Ko. and K.K.; supervision: M.Ku. and A.S.; project administration: M.Ku., M.Ko., K.K. and A.S.

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INTEGRACJA MODELOWANIA INFORMACJI O BUDYNKU (BIM) W BUDOWNICTWIE: INNOWACJE, WYZWANIA I GLOBALNE PERSPEKTYWY

STRESZCZENIE

Współczesny przemysł budowlany przechodzi transformacyjne zmiany napędzane powszechną cyfryzacją, stąd modelowanie informacji o budynku (BIM) staje się kluczową innowacją. W niniejszym artykule udowodniono konieczność włączenia BIM do każdego nowego projektu budowlanego, podkreślając jego potencjał w zakresie poprawy współpracy, usprawnienia procesów oraz wspierania innowacji. Poprzez kompleksową analizę piśmiennictwa w zakresie zastosowania BIM w Polsce i na świecie dokonano oceny różnorodnych narzędzi programistycznych i porównano metodyki BIM z tradycyjnymi praktykami budowlanymi. Dodatkowo w artykule zidentyfikowano możliwości i wyzwania związane z integracją nowych technologii w sektorze budowlanym. Konieczność wdrożenia BIM w celu zwiększenia efektywności, redukcji odpadów i poprawy wyników projektowych została potwierdzona empirycznie. Technologia BIM niezaprzeczalnie stała się elementarnym komponentem procesu tworzenia i zarządzania informacjami o obiekcie budowlanym w całym jego cyklu życia, wykorzystywanym w architekturze, inżynierii i zarządzaniu budownictwem.

Słowa kluczowe: modelowanie informacji o budynku, zarządzanie obiektem, rzeczywistość rozszerzona, wykrywanie kolizji, Revit, Archicad

ENVIRONMENTAL AND ARCHITECTURAL ASPECTS OF WOODEN CONSTRUCTION: A COMPARATIVE ANALYSIS OF SELECTED ISSUES OF SINGLE-FAMILY HOUSING IN POLAND AND PORTUGAL

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ABSTRACT

In the second half of the 20th century, it seemed that wooden architecture would be replaced by other, increasingly used, technologies. Wood was primarily used in hybrid systems, rather than as the dominant construction and finishing material. However, the turn of the 20th and 21st centuries reversed this trend. There is now a growing interest in wooden structures and finishes. Wood is becoming a “fashionable” material. This shift is influenced by new technologies that provide innovative construction possibilities, as well as by new methods of protecting wood. Wood is a renewable, ecological material with a small built-in carbon footprint, making it easy to recycle and suitable for a circular economy. The aim of the study is to compare the features of wooden single-family houses in Poland and Portugal. The methods necessary for this purpose were employed: critical analysis, observation without intervention and case studies to compare contemporary architectural trends. The results of research on current trends in shaping wooden single-family architecture allowed for drawing conclusions regarding formal, functional and pro-environmental solutions.

Keywords: wooden architecture, wooden construction, single-family house, climate crisis, sustainable development, circular economy

INTRODUCTION

Wood is one of the primary building materials. It has been with us since the beginning of the period when humanity began to create shelters (Xu, 2022). Wood was a material that was easy to obtain, transport, process. Most importantly, was renewable. As technology and sources of raw materials progressed, wood fell into the background, remaining a material for the internal partitions of buildings and roof structures, and then becoming a finishing material (Youngs & Hamza, 2016). Importantly, most pitched roof structures are made of wood. In the second half of the 20th century, wooden architecture as a structure made entirely of wood was in decline. The reason for this state of affairs was low competitiveness in relation to brick technologies. It is also crucial to consider the public's perception of wooden structures as having lower durability and the necessity for ongoing maintenance and repair of components that, if not adequately protected, are susceptible to biological deterioration. However, this trend did not change on a large scale

at the turn of the 20th and 21st centuries (Viholainen et al., 2021a). We are currently observing an increased interest in wooden structures. This is primarily due to the growing ecological awareness of users and, no less importantly, also to the search for alternative technologies in relation to the traditional ones, as masonry structures are called. This search results primarily from an attempt to reduce construction costs, not only in terms of material prices, but also labour inputs and the time needed to construct the building (Branco & Alves, 2020). The trend of returning to wooden structures is noticeable (Viholainen, Kylkilahti, Autio & Toppinen, 2020), but not dominant; wood is becoming “fashionable” again, but full trust is not yet there (Lähtinen, Harju & Toppinen, 2019; Viholainen et al., 2021a). An opportunity to increase the share of wooden structures in the market is emerging through new technologies that can compete with masonry structures, providing much greater opportunities than traditional wooden construction (Alves, 2022; Dukarska & Mirski, 2023) and new methods of securing wooden structures that ensure modern utility and fire protection requirements are met. A building is classified as wooden when its supporting structure and most of its components are made of wood. We can mention here materials based on chips (laminated strand lumber – LSL and parallel strand lumber – PSL), glulam beams and columns, cross-laminated timber – CLT, mechanically joined timber – NLT and construction timber – KVH (De Araujo et al., 2016; Almeida, Barbosa & Malheiro, 2020; Lechón, La Rúa & Lechón, 2021; Tavares & Freire, 2022). What is important is its low built-in carbon footprint and the fact that it is an ecological material that can be easily recycled (Buchanan & Levine, 1999; Geng, Yang, Chen & Hong, 2017; Monteiro, Freire & Fernández, 2020; Mendonca & Vieira, 2022; Valyova, Parzhov, Hua & Koynov, 2023).

Nowadays, the construction sector is responsible for a significant part of the negative impact on the environment (Zabalza Bribián, Valero Capilla & Aranda Usón, 2011; Grygierek & Ferdyn-Grygierek, 2022). Its share in total emissions is 42% in the case of energy consumption, 50% in the case of greenhouse gas emissions and 22% of the total amount of waste in 2020 (Coelho & Brito, 2013; Onat & Kucukvar, 2020). In this context, the European Union establishes targets and policies to reduce the environmental impact of the construction sector (Wang, Toppinen & Juslin, 2014; Vilčeková, Čuláková, Burdová & Katunská, 2015; Morton, Pencheon & Bickler, 2019). Wood has an advantage over other building materials, mainly masonry and steel structures, due to the fact that it is a renewable material, it binds carbon dioxide during tree growth and provides more optimised and cleaner forms of construction than other technologies (Börjesson & Gustavsson, 2000; Gustavsson, Pingoud & Sathre, 2006; Høibø, Hansen & Nybakk, 2015; Heräjärvi, 2019; Amiri, Ottelin, Sorvari & Junnila, 2020; Schau, Niemelä, Niemelä, Alencar Gavric & Šušteršič, 2022).

There are regions where traditionally smaller buildings, mainly residential ones, are made of wooden structures. A significant rate of such constructions occurs in countries such as the United States of America (90–94%), Canada (76–85%), the Scandinavian countries (80–85%) and Scotland (approximately 60%). These countries have a rich tradition of this form of construction. It should be borne in mind that wooden structures must be adapted to the specificity of a given country. Important factors here include climatic conditions (dry or wet environments), the wood’s greater susceptibility to biological conditions and access to good quality wood, which also ensures the renewable resources to meet the demand for the raw materials (Quintana-Gallardo, Schau, Niemelä & Burnard, 2021). In the absence of a continuing tradition of wooden structures in most countries, factors such as the lack of experience in the construction industry, a lack of developed wood processing technologies, unspecialised workers, low awareness of the design and construction sector, as well as a lack of detailed regulations and standards, will be important (Arlet, 2021; Viholainen et al., 2021b).

Wooden constructions in Portugal and Poland have a rich tradition from the 13th to the 20th century. Mixed construction solutions were most often used, because wood was rarely utilised as the only material in buildings, being most often applied as a complement to a stone masonry structure (Marcal Goncalves, Perez Cano & Rosendahl, 2019). Therefore, currently, the number of wooden buildings is relatively small

in the country. The result is that a small number of companies have specialised in wooden buildings. These are usually small construction companies specialising in this type of construction (Departamento de Edifícios Núcleo de Arquitectura e Urbanismo, 2011). This is compounded by the fact that a significant portion of wooden products in Portugal is imported as raw materials or components of ready-made solutions (Lerink et al., 2023). In Poland, unlike in Portugal, the supply of wood was abundant, which facilitated the development of wood-based structures (Terlikowski, 2022).

Table 1. Population and area

Specification	Poland	Portugal	Ratio
Area [km ²]	322 575	92 152	1/3.5
Population [million residents]	37.75	10.33	1/3.6

Source: Główny Urząd Statystyczny database; Instituto Nacional de Estatística database.

Table 2. Forests' area

Forest resources	Poland	Portugal	Ratio
Per 1 000 ha	8 331	2 199	1/3.7
Per capita	0.22	0.21	1/1

Source: Forest Europe (2020).

Table 3. Wood production

Specification	Poland	Portugal	Ratio
Roundwood [1 000 m ³]	46 586	13 957	1/3.3
Sawnwood [1 000 m ³]	5 190	1 140	1/4.5

Source: Food and Agriculture Organization of the United Nations (2018).

As early as the 1980s, it was discovered that architects bear greater responsibility for the state of the natural environment than other professional groups. Pro-environmental design, in addition to direct and indirect benefits for the environment, also leads to better health and well-being for users. Design decisions influence the architectural form of structures, as well as the effectiveness of implementation and operating costs (Stasiak-Betlejewska & Potkány, 2015).

In light of this, the present article aims to compare wooden architecture, taking into account single-family houses in two countries at the opposite ends of the European Union: Poland and Portugal. Such a comparison is justified by significant differences, not only cultural and geographical ones, but also resulting climate factors such as differences in temperature, humidity, hours of sunlight and amount of rainfall. These countries also differ in terms of vegetation (i.e., raw materials, technologies, methods of design and construction, as well as the way of planning space and using buildings). The purpose of this is to compare and show differences and common points, which is intended to help in planning activities aimed at promoting and developing the wooden construction sector for both geographies.

MATERIAL AND METHODS

The following research methods were adopted: critical analysis method, observation method (without intervention), case study and comparative analysis of contemporary architectural trends. In contemporary architecture, it is difficult to talk about styles due to the fact that designers avoid clear definitions and attempts to assign them to a clearly defined style. The language of architecture is diverse, but user expectations are also aesthetically diverse. Historical periods usually had a consistent definition of beauty for a given era; today, it has many variations. Hence, the terms “trend” is used more often than “style”. The work used publicly available materials regarding the examined objects, as well as the designers’ own materials. Formal and substantive criteria for selecting the research sample were adopted, and comparable criteria were applied to all research subjects.

Formal criteria for selecting the research sample

Formal criteria for the subject of research were determined based on the availability of materials in the following areas: location, year of implementation, designer and graphic material. The criteria were defined in detail and the assessment of their fulfilment described (Table 4). Comparable criteria were adopted for all research subjects.

Table 4. Formal criteria for selecting the research sample

No	Criterion name	Criterion definition	Description of the criterion
1F	Location	The evaluation criteria will include: – for all research subjects – the ability to determine at least the country and city.	1. Obligatory criterion. 2. Assessment of the fulfilment of the criterion involves assigning the logical value “yes”.
2F	Year of implementation	The evaluation criterion will include the possibility of determining the year of implementation.	
3F	Designer	The evaluation criterion will include the possibility of identifying at least the design studio and/or the author(s) of the project.	
4F	Graphic material	The evaluation criterion will include the possibility of obtaining the following for the research subjects: – at least one illustration of the exterior, – at least one interior illustration, – floor plans of all residential floors.	

Source: team’s fieldwork.

Substantive criteria for selecting the research sample

The substantive criteria of the subject of research were divided into general (function of the building, independence of the building, year of construction of the building, structure and finishing materials) and classification (type of location, contemporary formal and aesthetic trends, contemporary functional/ /spatial trends and contemporary pro-environmental trends). The criteria were defined in detail, and the assessment of their fulfilment was described (Table 5). Comparable criteria were adopted for all research subjects.

Table 5. Formal criteria for selecting the research sample

No	Criterion name	Criterion definition	Description of the criterion
General substantive criteria			
1M	Building function	The evaluation criteria will include: – residential function, – original residential function.	1. Obligatory criterion. 2. Assessment of the fulfilment of the criterion involves assigning the logical value “yes”.
2M	Building independence	The assessment criterion will include the independence of the building for its residential function: – single-family detached building.	
3M	Year of construction of the building	The dating criteria will include: – 21st century.	
4M	Construction	The following criteria will be assessed based on the building structure: – wooden structure, – hybrid structure, dominantly wooden.	
5M	Finishing materials	The criteria for evaluation will include the building’s finishing materials: – wood as the dominant material.	
Substantive classification criteria			
1K	Location type	The evaluation criteria will include the type of location: – downtown, urban, – on the outskirts (peripheral), outside the city.	1. Obligatory criterion. 2. Assessment of the fulfilment of the criterion involves assigning the logical value “yes”.
2K	Contemporary formal and aesthetic trends	As part of the classification criterion, the following will be assessed: – features of contemporary trends/currents, – features of pro-environmental architecture.	1. Optional criterion. 2. Assessment of fulfilment of the criterion consists in assigning the logical value “yes” to at least one group.
3K	Contemporary functional and spatial trends	The criterion will verify the impact of: – cultural conditions, expected standard, legislation, – location and climate conditions, – climate crisis.	
4K	Contemporary pro-environmental trends	The evaluation criteria will include: – a place in line with the principles of sustainable development, minimising the impact on the environment, – materials and/or innovative pro-environmental technologies, including: • use of materials that do not disturb the balance of environmental resources, • effective use of water resources, • efficiency of heating systems.	

Source: team’s fieldwork.

RESULTS

Nowadays, the profession of an architect is not limited only to design; it requires knowledge of research tools, among other things, in order to conduct interdisciplinary pre-design research before each new task. On the other hand, a new research trend in architecture is being formed – research through design. So far, the vast majority of research has been theoretical. In times of climate crisis and global social and economic problems, this approach seems to be insufficient. Practice-related research, defined as research by design, evidence-based design or action research, assumes that during design, knowledge is generated to solve a specific research problem (European Association for Architectural Education [EAAE], 2022).

Research on single-family residential houses located in Poland and Portugal

Single-family residential buildings that can obtain the status of exemplification of the thesis were selected for the study based on the established criteria. The subject of the research is a contemporary single-family residential building, constructed in a wooden or mixed structure, but with a predominant share of wood.

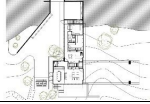
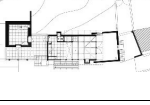
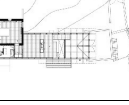
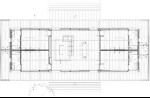
The territorial and temporal scope of the research was defined as Poland and Portugal during the 21st century. The examined facilities in both countries are listed in Tables 6 and 7.

Table 6. Surveyed single-family residential houses located in Poland

Object number	Basic information about the object	Photography - formal and aesthetic solutions	First floor plan - functional and spatial solutions	Second floor plan - functional and spatial solutions
• 01PL • House Behind The Roof	• Location: Poland, Kraków • Year: 2018 • Area: 189 m ² • Architects: Superhelix Pracownia Projektowa			
• 02PL • One Family House "Dr House"	• Location: Poland, Rosnówko • Year: 2018 • Area: 240 m ² • Architects: minimalDesign			not applicable
• 03PL • Kashubian House	• Location: Poland, Gowidlino • Year: 2016 • Area: 67 m ² • Architects: Grzegorz Layer			
• 04PL • Wooden House on a Meadow	• Location: Poland, Greater Poland • Year: 2020 • Area: 150 m ² • Architects: Ultra Architects			not applicable
• 05PL • House View on Brodnica Landscape Park	• Location: Poland, Pokrzydowo • Year: 2017 • Area: 160 m ² • Architects: House of Architects			not applicable
• 06PL • Cedar House	• Location: Poland, Poznań • Year: 2013 • Area: 166 m ² • Architects: Mariusz Wrzeszcz Office			not applicable
• 07PL • Standard House	• Location: Poland, Pszczyna • Year: 2011 • Area: 224 m ² • Architects: KWK PROMES Robert Konieczny			
• 08PL • Poz 7 House	• Location: Poland, Poznań • Year: 2019 • Area: 272 m ² • Architects: PLArchitekci			not applicable
• 09PL • Field House	• Location: Poland, Głogów • Year: 2016 • Area: 175 m ² • Architects: Blank Architects			not applicable
• 10PL • The Farm-house	• Location: Poland, • Year: 2021 • Area: 507 m ² • Architects: BXBstudio Bogusław Barnas			

Source: team's fieldwork.

Table 7. Surveyed single-family residential houses located in Portugal

Object number	Author's name of the building	Basic information about the object	Photography - formal and aesthetic solutions	First floor plan - functional and spatial solutions	Second floor plan - functional and spatial solutions
• 01PT • Columba Tree House	• Location: Portugal, Melides • Year: 2022 • Area: 258 ft² (23.97 m²) • Architects: Madeiguincho				
• 02PT • Chestnut House	• Location: Portugal, Vale Flor • Year: 2020 • Area: 25 m² • Architects: João Mendes Ribeiro			not applicable	
• 03PT • Expansion of Barrocas House	• Location: Portugal, Estremoz • Year: 2017 • Area: 150 m² • Architects: Carlos Castanheira			not applicable	
• 04PT • House Quinta do Buraco III	• Location: Portugal, Cucujães • Year: 2001 • Architects: Carlos Castanheira + Clara Bastai				
• 05PT • Casa Costa Grande	• Location: Portugal, Baião • Year: 2012 • Architects: Carlos Castanheira				
• 06PT • Casa Avenal	• Location: Portugal, Avenal • Year: 2004 • Architects: Carlos Castanheira			not applicable	
• 07PT • House in Baião	• Location: Portugal, Baião • Year: 2021 • Area: 243 m² • Architects: raço Alternativo Arquitectos Associados				
• 08PT • Mima House	• Location: Portugal • Year: 2021 • Architects: Marta Brandão + Mário Sousa			not applicable	
• 09PT • Eco Tróia Resort – Casa II	• Location: Portugal • Year: 2020 • Area: 300 m² • Architects: GSS arquitectos				
• 10PT • Sister's House	• Location: Portugal, Penafiel • Year: 2018 • Area: 264 m² • Architects: Balthazar Aroso Arquitectos			not applicable	

Source: team's fieldwork.

Recapitulation of research results

The adopted substantive classification criteria were used to draw up detailed conclusions for further research (comparison of Table 5):

- 1K – Each location is different and requires a separate, in-depth analysis and decisions regarding formal and functional solutions in connection with pro-environmental solutions. The analysed facilities are located on the outskirts of the city or outside the city. This is the preferred type of location for wooden single-family houses; globally, new wooden buildings located in city centres are rare.
- 2K – The design solutions are similar and are based on a frame structure (Almeida De Araujo et al., 2016; Monteiro, Freire & Fernández, 2020). There were no significant implementations in other wood-based technologies such as CLT or log structures. Of course, such implementations exist, but they are not dominant. Visible differences in the construction of building partitions result from local conditions and the method of thermal insulation protection of buildings (Sousa, Bragança, Almeida & Silva, 2013; Brandão De Vasconcelos, Pinheiro, Manso & Cabaço, 2015). Due to climatic reasons, buildings in Poland are better protected against weather conditions in winter, which translates into a thicker number of layers within the building envelope or building enclosure. This is reflected in the form of the building. Projects in Portugal are characterised by lightness and greater freedom in creating space. The architectural form of buildings in Poland and Portugal differs, especially with regard to the roofs of the buildings. Projects in Portugal are characterised by flat or shed roofs with one slope. In Poland, they most often have a gable form, which can be related to the climate and current snowfall in winter, but also to historical conditions. Buildings in Poland often refer in their form to traditional agricultural buildings, often barns with a simple rectangular form covered with a gable roof. In the case of Portugal, the lack of timber references and the absence of 100% timber traditional buildings resulted in architectural freedom to explore and design other forms. All examined objects in Poland and Portugal are characterised by a strong architectural expression emphasising wood as the main building material. This is not obvious considering the possibility of using cheaper façade cladding. The use and emphasis of wood on the façades of the examined buildings results, among other things, from the desire to emphasise the natural character of the building. This is a manifestation, apart from aesthetic factors, of pro-ecological solutions resulting from the building's construction. This creates a trend to notice this type of investment, creating popularity and fashion for ecological construction among given communities (Stepien et al., 2022; Sano, Saito & Boontharm, 2023).
- 3K – The trends in shaping wooden buildings in Poland and Portugal in terms of functional solutions are similar. The functional division of living space and zoning into general/daytime and private/nighttime areas result from contemporary design trends and is universal for continental Europe. The functional layout dominates, with three bedrooms in the private/night zone. In the case of Portugal, more often than in Poland, one can observe a more extensive external part of the area functionally connected to the interior of the house. This is due to the climate and the longer period of time that allows for staying outdoors. Houses in Portugal are generally characterised by greater openness to the surroundings, most often through the use of large glazing in the living areas. In the case of Polish houses, the dominant feature is to allocate space for a garage for cars, which is also determined by the climate and winter protection (Morgado, Correia Guedes, Gomes Ferreira & Cruz, 2020).
- 4K – Contemporary wooden single-family buildings are designed and implemented with awareness of environmental problems. The location is not accidental; various ecological aspects are analysed in order to minimise the impact of the investment on the environment. Wood is an ecological, renewable material, which means it does not disturb the balance of environmental resources. Moreover, the case studies are characterised by efficient use of water resources through the harvesting and use of rainwater and, to a lesser extent, grey water. The examined facilities have various heating systems; most of them are energy-saving or passive. Most of them use renewable energy sources (RES) systems, mainly photovoltaic panels. Due to diverse location conditions, regional environmental priorities were taken into account in the design and implementation process.

On the basis of the analysed single-family buildings with wooden structures constructed in the 21st century and located in Poland and Portugal, an attempt was made to identify contemporary trends in shaping wooden residential architecture. The context of the place – urban, historical or natural – differs in each case. The single-family houses presented are mainly located mainly on the outskirts of cities or outside urban areas. They reference to local history or present universal aesthetic solutions. The natural context is crucial. It was necessary to ascertain whether, in connection with the above, it was possible to identify clear directions for shaping the architecture of wooden single-family houses and, if so, whether the conclusions could be described as general or specific. The authors aimed to indicate general directions based on their own observations and features important for designers highlighted in the authors' descriptions, divided into two problem areas that often co-occur.

1. Formal-aesthetic and functional-spatial trends – combinations of various types of shapes, more or less ordered, repeatable or single, related to greenery and terrain. Often shaped according to the principles of addition or subtraction, mainly of cubic elements, but also of rotational forms or displacements of solids relative to each other. Moreover, the examined objects can be classified according to their essential and common features: contextual and acontextual/universal, compact and fragmented, atrial and opening to the surroundings, single-storey and two- or more-storeys, modular and non-modular/single-storey.
2. Pro-environmental trends – all facilities examined were designed with ecological sensitivity in the context of the climate crisis, but the assumptions translate into implementation solutions to varying degrees. The importance of such solutions also varies, but the direction of ecological/sustainable architecture and the related bioclimatic architecture is clearly evident. The principle is the design of single-family residential buildings in functional harmony with the surrounding natural environment, making maximum use of its natural conditions without negative intervention and ensuring full comfort for all users in a friendly space.

DISCUSSION

Wooden house constructions in Poland and Portugal have a rich tradition. Based on the study's findings, it was found that in Portugal, the entire structure was less often made of wood and more often used wood as a cladding material, which was mainly due to the availability and ease of obtaining raw materials. This influenced the construction methods and the character of the architecture compared to Poland, where wood was a widely material (Silva, Mendonça & Branco, 2012).

Nowadays, the great importance of wooden structures in the context of climate change (Sulaiman, Abdul-Rahim & Ofor, 2020; Rybak-Niedziółka et al., 2023), circular economy solutions (Kaziolas, Zygomalas, Stavroulakis & Baniotopoulos, 2013; Łacek & Starzyk, 2023), especially in relation to the Green Deal arrangements for the European Union area (Sikkema, Styles, Jonsson, Tobin & Byrne, 2023), is indicated. Prefabricated solutions in particular should be pointed out here, which may make such solutions more widespread due to their lower price and speed of installation (Araujo et al., 2022; Tenório, Branco & Silva, 2023; Švajlenka & Kozlovská, 2023). The main future solution is a system based on CLT (Balasbaneh & Sher, 2021; Krzosek & Kłosińska, 2021; Leszczyszyn et al., 2022). Both in Poland and Portugal, there is a market and realisations of such solutions (Oliveira, Couto, Mendonça, Silva & Reis, 2013; Radziszewska-Zielina & Gleń, 2014). These markets differ in housing issues, but common features can be found in terms of housing space requirements (Rącka & Khalil Ur Rehman, 2018; Instituto Nacional de Estatística, 2022; Starzyk et al., 2023).

The main differences that can be demonstrated are due to solutions resulting from climatic conditions. In the case of Poland, it is necessary to use more resistant buildings to the effects of mainly low temperatures, which is not left without an impact on the external form (Grygierek et al., 2020).

CONCLUSIONS

The authors conducted architectural research on single-family buildings with wooden structures in Poland and Portugal. The projects examined were created in the 21st century. Poland and Portugal differ in their geographical location, climate, land area and population. These factors influence the development of buildings and the adopted technological solutions adopted. However, some commonalities can be identified. One should begin by comparing conditions based on area, population and estimated forest production for construction purposes. Considering the proportion of differences in these indicators, it can be noted that Poland and Portugal are similar in terms of population density and the area of wood resources per inhabitant. A similar proportion was obtained when comparing the domestic production of wooden assortments and sawmill wood (Forest Europe, 2020). This allows us to conclude that, despite geographical, economic and social differences, Poland and Portugal have similar conditions for the development of the construction sector based on wooden structures (Nunes, Meireles, Pinto Gomes & De Almeida Ribeiro, 2019).

The results of research on contemporary trends in shaping wooden single-family architecture allowed for drawing general conclusions regarding formal solutions. The dominant forms are based on a combination of various shapes, repeatable or single, more or less ordered, often shaped on the basis of addition or subtraction. Houses take into account the context of the place; relatively few can be classified as acontextual. Mostly, they are related to the topography and greenery, taking into account the pro-environmental factor. The above important and common formal features served as the basis for the author's classification of contemporary wooden single-family houses into two main trends – neo-vernacular and neo-modernist. There are objects created with reference to the features of other trends, but these are rare cases. Both main trends can and most often coexist with the ecological trend.

Polish and Portuguese people are aware of climate change and the need to reduce the environmental burden of the construction sector (Correia Guedes, Pinheiro & Manuel Alves, 2009; Lee, Markowitz, Howe, Ko & Leiserowitz, 2015). Hence, there are more and more ecological solutions with wooden structures in these areas. This is not a dominant trend; traditional construction methods are still the most popular. This is still due to the lack of trust in wooden structures, the lack of specialised companies and the low price competitiveness of building a wooden house compared to traditional solutions (Viholainen et al., 2020; Palma, Gouveia & Barbosa, 2022). This applies equally to Poland and Portugal, despite the relatively good and comparable conditions of both countries for the development of the wooden building construction sector.

While Polish and Portuguese people are aware of climate change and the need to reduce the construction sector's environmental footprint, increasing the share of wood presents a potentially viable solution. Although there are challenges – such as timber construction not being a dominant trend and trust in its structural integrity not yet being fully established – a long-term perspective reveals significant environmental benefits without compromising the buildings architectural and construction quality of buildings. Consequently, discussions on incentives for wood construction incentives through government policies or awareness sensibilisation campaigns should be pursued with the aim of broader implementation.

Authors' contributions

Conceptualisation: A.S., N.D.C. and C.C.D.; methodology: A.S.; formal analysis: A.S., N.D.C. and C.C.D.; investigation: A.S.; writing – original draft preparation: A.S., N.D.C., C.C.D. and P.Ł.; writing – review and editing: A.S., N.D.C., C.C.D. and P.Ł.; visualisation: A.S., N.D.C., C.C.D. and P.Ł.; supervision: A.S. and N.D.C.; funding acquisition and project administration: A.S.

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ŚRODOWISKOWE I ARCHITEKTONICZNE ASPEKTY BUDOWNICTWA DREWNIANEGO: ANALIZA PORÓWNAWCZA WYBRANYCH ZAGADNIEN BUDOWNICTWA JEDNORODZINNEGO W POLSCE I PORTUGALII

STRESZCZENIE

W drugiej połowie XX wieku wydawało się, że budownictwo drewniane zostanie wyparte przez inne, coraz częściej stosowane technologie. Drewno było głównie stosowane w układach hybrydowych, nie jako dominujący materiał konstrukcyjny i wykończeniowy. Przełom XX i XXI wieku odwrócił tę tendencję. Obecnie obserwuje się zwiększone zainteresowanie konstrukcjami drewnianymi oraz wykończeniowymi drewnianymi. Drewno staje się materiałem „modnym”. Mają na to wpływ nowe technologie dające nowe możliwości konstrukcyjne, a także nowe metody zabezpieczania drewna. Drewno jest odnawialnym surowcem o małym wbudowanym śladzie węglowym, materiałem łatwym do recyklingu i do stosowania w gospodarce

o obiegu zamkniętym. Celem badania jest porównanie cech drewnianych domów jednorodzinnych w Polsce i Portugalii. Zastosowano metody niezbędne do założonego celu: analizy krytycznej, obserwacji bez interwencji, studium przypadku w celu porównania współczesnych trendów architektonicznych. Wyniki badań współczesnych trendów w kształtowaniu drewnianej architektury jednorodzinnej pozwoliły na wyciągnięcie wniosków dotyczących rozwiązań formalnych, funkcjonalnych i prośrodowiskowych.

Słowa kluczowe: architektura drewniana, budownictwo drewniane, dom jednorodzinny, kryzys klimatyczny, rozwój zrównoważony, gospodarka o obiegu zamkniętym

LABORATORY STUDIES ON THE EFFECTS OF OIL POLLUTION ON SOIL PROPERTIES

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ABSTRACT

Soil pollution is one of the world's most debated and widespread environmental issues. In particular, oil spills pose a significant global threat, with an environmental impact only slightly below that of radioactive contamination. This study conducted laboratory tests on the granulometric composition and consistency limits of soil samples artificially contaminated with engine oils. Three different types of engine oils were added to the soils in proportions of: 2.5%, 5% and 10% by dry weight of the soil sample, respectively. The trends in changes of the parameters determined due to pollution were evaluated. The study included a comparative analysis of the results of studies on the parameters of polluted soils carried out in Polish and foreign scientific centres. For silty sand (siSa), the content of the clay fraction decreased from an initial 7% to a range of 1–3%. For clayey sand (clSa), the content of the clay fraction decreased from 13% to a range of 1–7%. The plastic limit (*PL*) was 13.24% for siSa and 16.42% for clSa. The tested soils contaminated with engine oil were classified as non-plastic. The liquid limit (*LL*) for siSa and clSa was around 21%. The *LL* of siSa decreased from 21% to 15% due to contact with all types of engine oils. For clSa, the *LL* decreased to a range of 10–14%, depending on the type of engine oil. The results of this study highlight the engineering importance of understanding soil behaviour under oil contamination, which is crucial for assessing the stability and safety of structures in contaminated areas and for designing effective remediation strategies.

Keywords: oil spill, contamination, granulometric composition, consistency limit

INTRODUCTION

Oil compounds are among the most common soil contaminants due to extensive pipeline leaks, inadequate oil waste management and accidents at various stages of fuel transfer (Karthick, Roy & Chattopadhyay, 2019; Haghsheno & Arabani, 2022). Moreover, the activities of repair workshops, production facilities, military bases, landfills, power stations and the entire municipal infrastructure contribute to pollution from petroleum-based contaminants (Korzeniowska-Rejmer & Izdebska-Mucha, 2006).

The intensity and toxicity of oil spills were found to pose a global threat, with oil spills ranking second only to radioactive contamination in terms of environmental hazard (Tumanyan, Tyutyuma, Bondarenko & Shcherbakova, 2017). The extent of pollutants' migration in the soil–water system depends mainly on the properties of the soil and the type of pollutant (Biswas et al., 2018; Nartowska, 2023). If a pollutant penetrates vertically into the soil, some portion of it will be adsorbed by soil particles already in the vadose

zone. If the contaminant is light (e.g., petrol), it can move more freely between the soil particles and migrate further. Heavier substances, such as lubricants and diesel fuels of all types, have a limited ability to migrate (Yang et al., 2024).

Changes in soil parameters due to contamination have been documented in many studies (Izdebska-Mucha & Korzeniowska-Rejmer, 2009; Kicińska, Pomykała & Izquierdo-Diaz, 2022). One of these changes is in the granulometric composition. Polluted soil samples differ significantly in their content of individual fractions compared to model soil samples (Izdebska-Mucha & Korzeniowska-Rejmer, 2009; Czado, Korzeniowska-Rejmer & Pietras, 2010; Osinubi, Eberemu, Bello & Adzegah, 2012). Decreases or increases in the content of individual fractions in the soils, sometimes by as much as several tens of percent, primarily indicated a change in soil type. The main reason for this is that the admixtures of various chemical compounds (sulphur, heavy metals) found in contaminants, such as petroleum substances, which are destructive. They break down part of the bonds present in the particles of the soil skeleton. Soils with a high clay fraction are particularly susceptible to such destruction. Consequently, cohesive soils are the least resistant to chemical aggression, and it is mainly in these soils that the greatest changes in physical, chemical or mechanical properties can be observed (Rajabi & Sharifipour, 2019). Elsaigh and Oluremi (2022) discovered that the geotechnical characteristics of highly cohesive soil are significantly influenced by hydrocarbon contaminants, regardless of their source, in comparison to granular soils. They also found that despite the soil's nature and mineral content, soils contaminated with hydrocarbons exhibit a greater potential for collapse. This was also confirmed by studies on artificially contaminated soils and contaminated samples taken directly from the site.

Among the soil characteristics altered by oil contamination are (Korzeniowska-Rejmer, Motak & Rawicki, 1995; Izdebska-Mucha, 2005; Rakowska et al., 2012; Azam, Xiao, Mia, Rahman & Zaman, 2022):

1. Granulometric composition. Due to oil contamination, there are significant changes in the granulometric composition. The content of the sand and clay fractions decreases, while the content of the silt fraction increases.
2. Specific density and bulk density. When the soil is saturated with hydrocarbons, the values of specific density and bulk density decrease. Changes in these values, as well as changes in the granulometric composition, also affect the porosity of the soil. This can lead to soil settlements and numerous voids, especially if the soil has been in contact with the contamination for a long time.
3. Consistency limits. A decrease in plasticity is observed in cohesive soils. As a result of rolling tests, soils are usually classified as non-plastic.
4. Mechanical parameters. Based on many years of research on contaminated soils, changes in the mechanical parameters of the soils have been observed. These are mainly a decrease in soil cohesion (c), angle of internal friction (ϕ) and primary modulus of compressibility (M_0). All of these values decrease with increasing contaminant concentration. The shear strength (τ) of the soil also decreases.

In areas where industrial activities are common, or where spills have occurred, understanding how contamination affects soil behaviour is important for ensuring the safety and durability of engineering structures. Czado et al. (2010) showed that even a relatively small amount of oil contamination in sandy soils can lead to a significant reduction in the resistance of the subsoil beneath the foundation. They demonstrated that for 2% oil contamination, the reduction in foundation resistance is more than 15%, and for 10% contamination, the resistance value can be reduced by more than 50%. Analysis of these results clearly indicates that when designing foundations for facilities such as petrol stations or liquid fuel tanks, where the potential risk of soil contamination with oil substances is relatively high, additional increased partial safety factors are necessary.

The research findings show that the changes in the engineering properties of soils significantly increase settlement and negatively influence the subsoil's bearing capacity parameters. This demonstrates the need for an assessment of soil parameters prior to construction. It also indicates that soil properties should be reassessed, even in built-up areas, if they are contaminated, to evaluate the degree of soil degradation (Surygala, Śliwka, Kołwzan & Greinert, 2000; Iwanicka, Janiszewska & Koda, 2020). Investigating the engineering behaviour and properties of contaminated soil is essential for identifying the most effective remediation methods or other practical uses for contaminated soil (Haghsheno & Arabani, 2022).

Most of the literature on changes in soil parameters due to contamination is primarily documented for cohesive soils such as clays. However, there is a notable need to fill the knowledge gaps for other soil types to better understand their response to contamination. In addition, most of the literature focuses on the effects of diesel, motor oil or crude oil, while this research examines the impact of engine oil. This study contributes to the knowledge base of how different types of engine oil contamination affect various soil types, providing valuable insights for the development of effective remediation strategies.

In view of the above, the aim of this study was to investigate the changes in the basic properties (granulometric composition, consistency limits) of two types of soils contaminated with different engine oils in proportions of 2.5%, 5% and 10% of the dry weight of the soil. The hypothesis of this study was that the addition of engine oils would reduce the clay content and plasticity of the soil, thereby affecting its suitability for engineering applications.

MATERIAL AND METHODS

Tested soils

Two natural soil samples were used in the study. The first was silty sand (siSa). The second soil was clayey sand (clSa). The samples were collected in the Warsaw area. The tested soils were classified according to their granulometric composition based on the PN-EN ISO 14688-1 standard (Polski Komitet Normalizacyjny [PKN], 2018).

Oil used

During laboratory tests, the model soil samples were contaminated by three types of engine oil: Oil 1 ($\rho = 0.855 \text{ g}\cdot\text{cm}^{-3}$), Oil 2 ($\rho = 0.850 \text{ g}\cdot\text{cm}^{-3}$), Oil 3 ($\rho = 0.843 \text{ g}\cdot\text{cm}^{-3}$). Oils were added to the soil samples in proportions of 2.5%, 5.0%, and 10.0% by dry weight of the soil sample, respectively. The soil–engine oil mixtures were stored in closed containers for one month.

Soil analysis

The particle size distribution of the soils was analysed according to the PN-EN ISO 14688-1 standard (PKN, 2018). A combined approach of sieve analysis for the coarser fractions ($\geq 0.2 \text{ mm}$) and hydrometer (areometric) analysis for the finer fractions ($< 0.2 \text{ mm}$) was used. The liquid limit (*LL*) and plastic limit (*PL*) of the soils were determined according to the EN ISO 17892-12 standard (International Organization for Standardization [ISO], 2018). The *LL* was determined using the Casagrande apparatus, while the *PL* was measured using the standard rolling method. The analyses of *LL* and *PL* were carried out in duplicate for natural soil samples and samples contaminated with three different engine oils.

RESULTS AND DISCUSSION

Effect of oil contamination on soil particle size distribution

As a result of the study, changes were observed in the percentages of the different fractions, depending on both the type of engine oil and its concentration. In particular, a significant decrease in the content of the clay fraction was observed. For silty sand (siSa), the content of the clay fraction decreased from an initial 7% to values in a range of 1–3% (Table 1). For clayey sand (clSa), the content of the clay fraction decreased from 13%, to values in a range of 1–7% (Table 2).

Table 1. Fractional percentages according to the degree of oil contamination for siSa

Fraction	Before contamination [%]	After contamination with oil								
		Oil 1			Oil 2			Oil 3		
		2.5%	5.0%	10.0%	2.5%	5.0%	10.0%	2.5%	5.0%	10.0%
Clay fraction	7	3	1	1	1	2	1	1	2	1
Silt fraction	31	38	33	27	28	31	24	31	28	29
Sand fraction	62	59	66	72	71	67	75	68	70	70

Source: own work.

Table 2. Fractional percentages according to the degree of oil contamination for clSa

Fraction	Before contamination [%]	After contamination with oil								
		Oil 1			Oil 2			Oil 3		
		2.5%	5.0%	10.0%	2.5%	5.0%	10.0%	2.5%	5.0%	10.0%
Clay fraction	13	7	4	1	5	3	2	6	4	3
Silt fraction	25	18	16	11	15	14	10	23	19	16
Sand and gravel fraction	62	75	80	88	80	83	88	71	77	81

Source: own work.

It was observed that the higher the concentration of oil contaminants in the soil, the lower the content of the clay fraction. A study by Korzeniowska-Rejmer and Izdebska-Mucha (2006) also showed a clearly noticeable decrease in the clay fraction for soil contaminated with diesel (10%). The content of the clay fraction decreased, according to the cited study, from 15% to 12%. This relationship is due to the fact that the clay fraction is the least resistant to chemical aggression. Similar studies have been carried out in many foreign research centres. Al-Obaidy and Shaia (2019) showed negative changes regarding grain size and plasticity index. In addition, changes were noted regarding other mechanical properties, such as a reduction in the value of the angle of internal friction and a reduction in the value of shear stress. Izdebska-Mucha and Korzeniowska-Rejmer (2009) showed that cohesive soils (clays) contaminated with petrol and diesel oil take on the properties of fine-grained non-cohesive soils, which – in particular – excludes their use as insulating materials in landfill liners. According to Korzeniowska-Rejmer and Izdebska-Mucha (2006), the sand fraction in silts reduced from 27% to 10% due to 25% oil contamination. This was also confirmed by Bian, Liu, Cai, Chu and Tian (2016), who demonstrated the reduction (from 13.8% to 7.7–8.3%) of the sand fraction

in silty clay contaminated with 10% kerosene or diesel. The observed reduction in the sand fraction due to the breakdown of larger soil aggregates may be the result of long-term physical and chemical aggression.

The effects of the addition of engine oils to soils on its particle size distribution changes are presented in Figures 1 and 2. These changes in granulometric composition may also reduce the values of the geotechnical parameters responsible for the strength and deformability of the soil, thereby altering its properties as a building subsoil (Korzeniowska-Rejmer & Izdebska-Mucha, 2006).

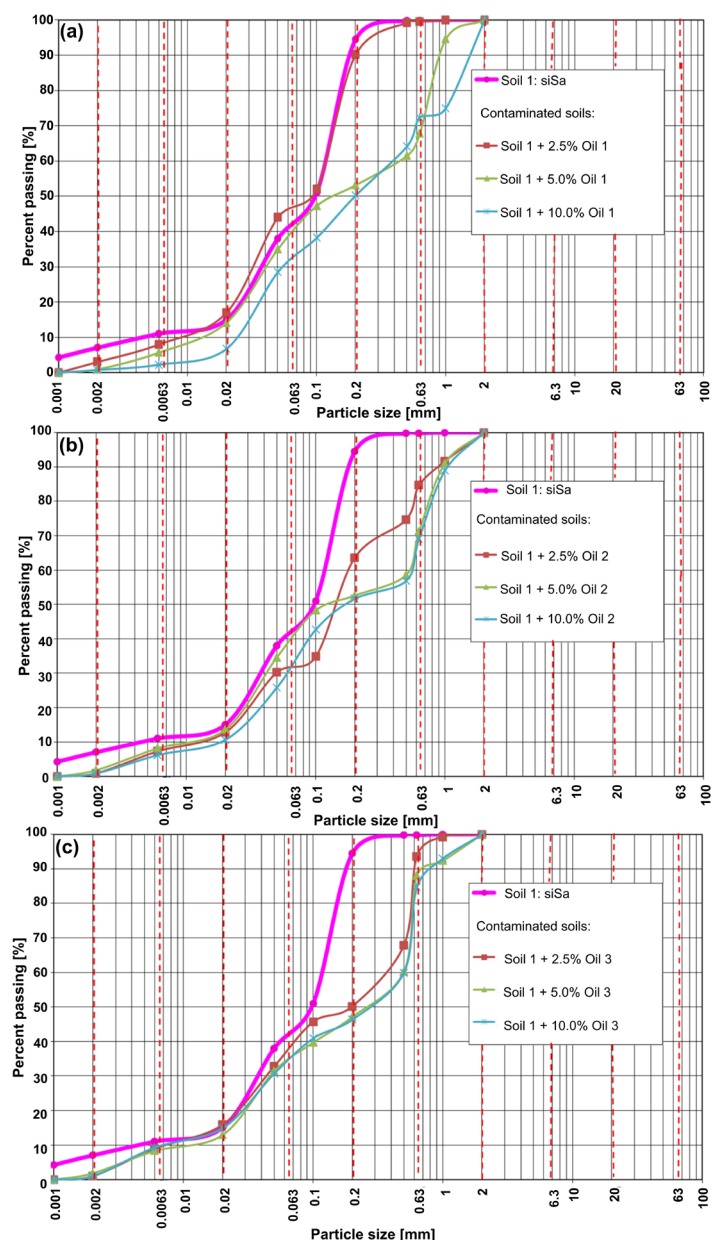


Fig. 1. Particle size distribution of siSa and soil–engine oil mixtures: (a) Oil 1, (b) Oil 2, (c) Oil 3

Source: own work.

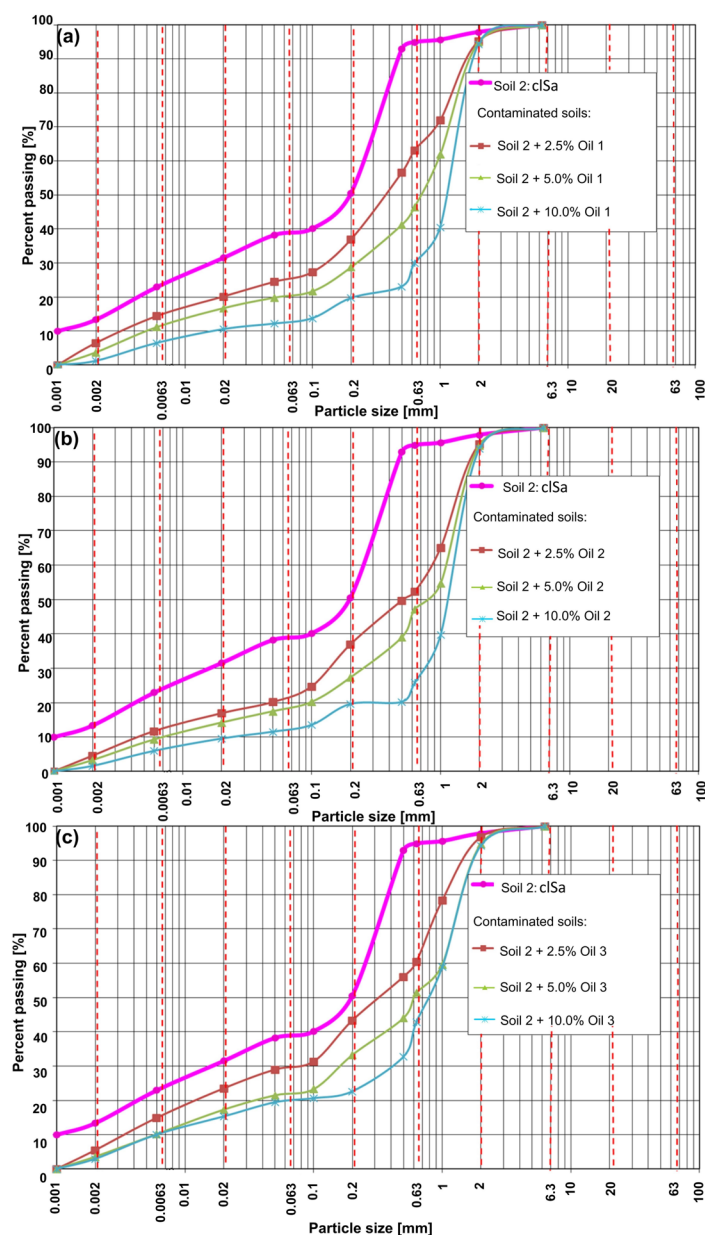


Fig. 2. Particle size distribution of cISa and soil-engine oil mixtures: (a) Oil 1, (b) Oil 2, (c) Oil 3

Source: own work.

Effect of oil contamination on plastic limit (PL)

In this study, the plastic limit was 13.24% for silty sand (siSa) and 16.42% for clayey sand (cISa). Soils contaminated with engine oil were classified as non-plastic. Similar studies were carried out by Korzeniowska-Rejmer and Izdebska-Mucha (2006), who showed that soils contaminated with oils could also be characterised as non-plastic. Similar conclusions were reached in a study by Izdebska-Mucha (2005), who showed that all clay samples tested after saturation with petrol were classified as non-plastic. Swaroop and Rani (2015) showed

a reduction in the *PL* from 35% for uncontaminated clay to about 22.5% for 5% oil-polluted clay and to about 13% for 10% oil-polluted clay. Tong, Chen, Zheng and Li (2012) revealed that both the *LL* and *PL* of clay loam changed to a less favourable state due to oil pollution. The results of their analysis lead to the same conclusions as those observed in the tests carried out in this study. Another example confirming that phenomenon is the work of Nazir (2011) and Akpokodje, Juwah and Uguru (2022), who clearly stated a decrease in *PL* and *LL* for oil-contaminated soils (over-consolidated clays). In a study by Jia et al. (2009), a completely different behaviour of coastal sediments under the influence of oil pollution was observed. The authors showed that the *LL*, *PL*, and plasticity index (*PI*) all increased with higher oil contamination levels. They concluded that the increase in Atterberg limits is due to the viscous nature of the pore fluid. In saturated fine-grained soils, the pore fluid occupies the voids within the soil structure and forms a thin layer between mineral contacts. This layer acts as a lubricant, allowing the soil particles to pack closer together. Lubrication at particle contact points is due to the viscosity of the pore fluid. As the viscosity of the pore fluid increases, it alters the interactions between minerals and pore fluid at the contact, making it harder to change the uniform state of the soil, which is reflected in the increased Atterberg limits. Also, according to Hewayde, Abbas and Kubba (2019), the increase in the percentage of engine oil in the soil resulted in an increase in the *PL* (from 15% to 21%) for organic silts and organic silty clays of low plasticity (symbol OL according to the Unified Soil Classification System; Casagrande, 1948).

Effect of oil contamination on liquid limit (*LL*)

The study showed that contamination with engine oil significantly affected the *LL* (Fig. 3). For the two uncontaminated soil samples (siSa and cISa) the *LL* was around 21%. For the samples contaminated with engine oil at a mass fraction of 10%, it decreased to values in a range of 14.5% to 15.4% for siSa and 9.6% to 16.2% for cISa.

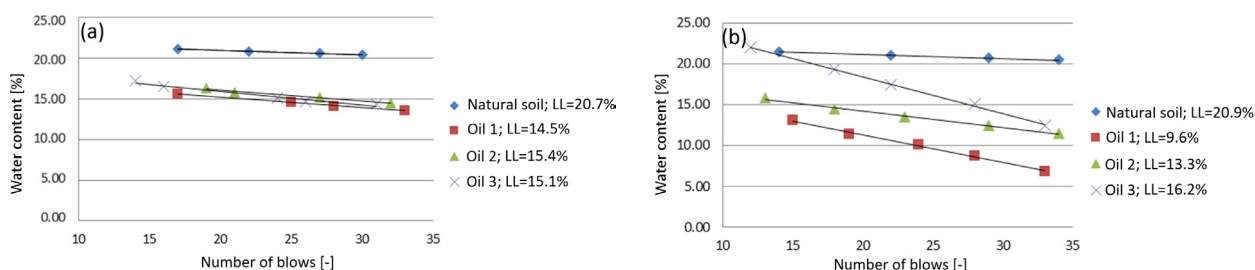


Fig. 3. Results of the Casagrande tests for natural soil samples: siSa (a) and cISa (b) and contaminated with the addition of three engine oils at a level of 10%

Source: own work.

The *LL* of the siSa decreased from 21% to around 15% regardless of the type of engine oil. For the cISa, the largest decrease in *LL* was observed due to contamination with Oil 1 (9.6%) and the smallest with Oil 3 (16.2%). Contact of the soil with Oil 2 decreased the *LL* to a level of 13.3%.

In comparison, Izdebska-Mucha (2005) tested several materials contaminated with petrol and diesel oil. In both cases, a significant decrease in the *LL* was observed compared to uncontaminated soils. For Neogene clays of the Poznań series, a decrease from 64% to 34–36% was observed. The *LL* of illitic clays was reduced from 46% to 24% (petrol pollution) and 26% (diesel oil pollution). For bentonite, a reduction in the *LL* was observed from 257% to 34% for petrol pollution and to 37% for diesel oil pollution. For kaolinite, the *LL* was reduced from 51% to 45% and 37% for petrol and diesel oil pollution, respectively. The smallest changes were observed for glacial till (*LL* reduction from 24% to 23% for diesel oil pollution; no reduction for petrol pollution).

Phougat (2017) observed similar relationships in a study on oil-contaminated clays. A significant decrease in Atterberg limits was observed for all contaminated samples. Both the *LL* and *PL* decreased, and the soils were characterised as non-plastic. A correlation of the intensity of changes with the duration of chemical aggression was also noted. The longer the samples were exposed to oil, the more their properties changed.

Hewayde et al. (2019) demonstrated that the increase in engine oil contaminant percentage resulted in a decrease in the *LL* of cohesive soils (*LL* = 44% for uncontaminated soil, *LL* = 43% for 5% engine oil content, *LL* = 41% for 10% engine oil content, *LL* = 39% for 15% engine oil content).

In a study by Akinwumi, Diwa and Obianigwe (2014), the addition of crude oil to the soil resulted in an increase in the *LL*, *PL* and *PI* of the contaminated sandy clay. This was attributed to the increase in the thickness of the diffuse double layer. The addition of crude oil to the soil decreased its permeability. This was attributed to the incorporation of crude oil into the pore spaces of the soil. This is partly in agreement with the study of Tong et al. (2012), who showed that the Atterberg limits of diesel-contaminated clay loam decrease with increasing oil content while the *PI* changes slightly. They found that the ‘pseudo-viscosity’ caused by crude oil leads to a decrease in *PL* and an increase in *LL*.

CONCLUSIONS

The influence of engine oil on soil properties is considerable, particularly on the content of individual soil fractions. This study has shown that engine oil-contaminated soils behave similarly to non-cohesive soils. In particular, the presence of petroleum substances significantly reduces the liquid limit and causes engine oil-contaminated soils to be classified as non-plastic.

Based on these findings, it is advisable to consider the significant changes in soil properties when designing engineering structures in areas contaminated by engine oils. The observed reduction in clay content and plasticity in contaminated soils could affect their bearing capacity and overall stability. Consequently, modified engineering approaches and remediation strategies may be necessary to effectively address these altered soil properties.

While this study provides valuable insights into the effects of engine oil contamination on silty sands and clayey sands, further research is needed. Future studies should investigate the behaviour of oil contaminants across a wider range of soil types. In addition, it is essential to examine the long-term effects of oil contamination, including its evolution over time and the potential for progressive degradation or chemical transformation of the contaminants. Further research should also explore the combined effects of multiple contaminants and their interactions with different soil types in order to develop more effective remediation techniques and engineering solutions for industrially degraded sites.

Authors' contributions

Conceptualisation: A.P. and A.G.; methodology: A.P.; validation: A.P.; formal analysis: A.P. and A.G.; investigation: A.P. and A.G.; resources: A.P.; data curation: A.P. and A.G.; writing – original draft preparation: A.P. and A.G.; writing – review and editing: A.P.; visualisation: A.P. and A.G.; supervision: A.P.

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

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BADANIA LABORATORYJNE WPŁYWU ZANIECZYSZCZEŃ OLEJOWYCH NA WŁAŚCIWOŚCI GRUNTÓW

STRESZCZENIE

Zanieczyszczenie gruntu jest jednym z najbardziej dyskutowanych i powszechnych zagadnień środowiskowych na świecie. W szczególności wycieki oleju stanowią znaczące globalne zagrożenie, a ich wpływ na środowisko jest jedynie nieco mniejszy niż w przypadku skażenia radioaktywnego. W niniejszej pracy przeprowadzono badania laboratoryjne składu granulometrycznego i granic konsystencji próbek gruntów sztucznie zanieczyszczonych olejami silnikowymi. Do gruntów dodano trzy różne rodzaje olejów silnikowych w proporcjach: 2,5%, 5%, 10% w stosunku do suchej masy próbek gruntów. Oceniono tendencje zmian właściwości gruntów pod wpływem zanieczyszczeń. W pracy dokonano analizy porównawczej wyników badań parametrów gruntów zanieczyszczonych prowadzonych w polskich i zagranicznych ośrodkach naukowych. W przypadku piasku z pyłem (siSa) zawartość frakcji ilastej (Cl) zmniejszyła się z początkowych 7% do zakresu 1–3%, w przypadku piasku z iłem (clSa) zawartość frakcji Cl zmniejszyła się z 13% do zakresu 1–7%. Granica plastyczności (w_p) wynosiła 13,24% w przypadku siSa i 16,42% w przypadku clSa. Badane grunty zanieczyszczone olejem silnikowym zostały sklasyfikowane jako nieplastyczne. Granicę płynności (w_L) na poziomie 21% oznaczono w przypadkach siSa i clSa. Granica płynności siSa zmniejszyła się z 21% do około 15% na skutek kontaktu ze wszystkimi rodzajami olejów silnikowych. W przypadku clSa granica płynności zmniejszyła się do zakresu 10–14% w zależności od rodzaju oleju silnikowego. Wyniki tej pracy podkreślają inżynierskie znaczenie zrozumienia zachowania się gruntu pod wpływem zanieczyszczenia olejowego, co ma kluczowe znaczenie przy ocenie stabilności i bezpieczeństwa konstrukcji na zanieczyszczonych obszarach oraz dla projektowania skutecznych strategii remediacji.

Słowa kluczowe: wyciek oleju, zanieczyszczenie, skład granulometryczny, granica konsystencji

PECULIARITIES OF FUNCTIONAL AND PLANNING ORGANISATION OF UNIVERSITY LIBRARIES

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ABSTRACT

A university library is a space in which complex organisational processes take place, various functional areas are intertwined and separate movement schedules coexist. If the library's physical space does not provide appropriate conditions for individual and group work, quick and free access to information resources or the possibility of using computers and copying equipment, such a library will be infrequently visited. All of this determines the specifics of the library's internal space organisation. To ascertain this, one needs to rethink its planning structure from the standpoint of possible functional development. That is why the essay's objective is to highlight the main functional and planning elements of a modern library, the presence or absence of which directly affects the quality of its functioning.

Keywords: university library, functional planning organisation, reading room, book depository, service room

INTRODUCTION

The history and architecture of university libraries have developed over many decades, even centuries. Their most distinguishing feature is a disproportionate organisation of space, with one large reading room, while other internal premises are usually dark, cramped and do not meet the modern requirements of the time or user needs. Such libraries are characterised, among other things, by unorganised infrastructure, outdated equipment, inefficient use of space, crowded book racks, inconvenient workrooms, unorganised planning and unsuccessfully designed service areas (Samotyj & Voronkova, 2014).

At the turn of the 20th and 21st centuries, dramatic changes in the awareness of the role and importance of a library as an institution took place. Whereas earlier, the library reflected a traditional concept of a repository, and its internal spaces were mainly intended for the accumulation, processing and storage of printed books. Today, the university library is more than just the centre of student life; it is open and accessible to the public at large. This is why new functions and spaces such as exhibition galleries, cafés, museums and lecture halls have emerged within the structure of the university library. Thus, its architecture becomes open, both conceptually and physically. This allows the library to be transparent in terms of its goals and functions (Wysokińska-Gąsior, Ed., 1995).

Constant technological development inevitably changes the library space. Library buildings of the 21st century adapt and improve functional planning organisation in accordance with new criteria in architecture and design,

actively introducing information technologies into their activities. In this way, the modern library space reflects a user-centred design product that supports social and educational models of learning and teaching and makes a positive contribution to the life of the city through its new iconic architecture (Nur Şanlı & Sirel, 2022).

The idea of open and accessible space in the library dates back to the 1960s. At that time, librarians first proposed to organising the functional and planning structure of the library as a ‘one-room library’. The approach implies that all library units are housed in the same room, separated from each other by furniture and book racks only. In addition, with such planning, three main areas can be distinguished: the core of the library (subscription, reading rooms, adult and children’s departments grouped around one department), administrative premises, and premises for cultural and educational events (Svobodová, 2012; Svobodová, 2014).

An interesting approach to zoning the library space was used by French specialists: they suggested using the concept of a ‘vaguely divided space’ rather than the term ‘boundary’ of the zone. They noted that in order for different groups of readers to coexist side by side, without interfering with each other, and to outline the content of the library space, it is necessary that the building’s planning structure is dominated by open spaces. In other words, the layout should contribute to the creation of different reading areas without establishing clear boundaries between them (Balashova, Tyshchenko & Vaisiev, 2004).

Today, the trends in internal planning of the library space focus on flexible interior options based on the use of modular structures with a minimum number of load-bearing walls. This provides the best conditions for modelling the space to perform the main functions of the library and to develop some new ones (Voronkova & Proskuryakov, 2020).

FINDINGS AND DISCUSSION

The analysis of international experience in the design and construction of library buildings allowed to identify two main functional blocks: the socio-cultural block and the library block.

The **socio-cultural block** (socioblock) is a free access area for library visitors to rooms and services designed for socio-cultural use. An important feature of the functional structure of modern university libraries is the presence of a social block, with additional units to serve regular users and temporary visitors. The basis of these units is the premises and individual structural elements, whose functioning is classified by the type of service provision. The premises are divided into two groups: commercial and non-commercial (Fig. 1).

To provide commercial services in the structure of the library’s social block, areas are allocated for the functions of food catering (café, buffet, restaurant), commerce (bookshop, stationery shop, souvenir shop), banking services (bank branches, cash machines, bank terminals), and office facilities.

Non-commercial services in the structure of the library’s social block are offered by the reception desk, subscription desk, wardrobe, information boxes, electronic catalogue, book return point, exhibition, museum, conference room, recreation area and round-the-clock operations areas.

To speed up the registration process of new users and to ensure timely receipt of pre-ordered books by regular users, a place is allocated in the library structure for the *registration point* and *book distribution point*. In small libraries, the registration and lending of books are carried out behind a common counter; large libraries may separate those two processes. In modern libraries (provided that the library is located in a separate building), the reception and subscription are placed on the ground floor, near the entrance to the library, providing a vertical connection to the main book depository. It is also equipped with shelves for the ordered items.

The *wardrobe* is usually placed directly at the entrance to the library. Sometimes, the wardrobe can be placed on the underground level in the library (if the library is located in a separate building) or moved outside the library, for example, in the corridor of the educational building. Recently, the wardrobe has acquired the features of self-service: fixed hangers and maintenance personnel have been replaced by individual lockers.



Fig. 1. Functional and planning elements of the socio-cultural block

Source: own work.

Information boxes and an electronic catalogue are installed in the library lobby (if the library is located in a separate building) or at the entrance to the library (within the library or outside, such as in the corridor of the educational building) for visitors to receive information about the library's activities or for quick access to the electronic catalogue.

The *book return point* is designed to receive user-processed literature received on subscription terms. The process of returning books can occur in different ways: assisted by the library employee, who accepts the returned items, or assistance-free, with no need to contact the library staff.

The *exhibition* and the *museum* perform the function of exhibiting works of fine art, equipment, new arrivals, bestsellers, rare editions, etc. Mobile stands, prefabricated demountable structures or cornices are used for exhibition displays. In small libraries, exhibitions can be set up in lobbies, on the walls of staircases, in the subscription room, or in the book distribution area. In large libraries located in separate buildings, a dedicated room for the exhibitions can be allocated (some libraries have specific rooms for exhibitions and museums), with an area ranging from 100 m² to 300 m². The main requirements for exhibition halls and museums include ensuring proper orientation with respect to horizon. Windows should face northwards to provide natural lighting and protect the exhibits from excessive insolation (Balashova et al., 2004).

The conference room. The minimum area of the lecture hall should be at least 50–60 m²; for cultural and entertainment events, the area of the hall should be at least 200 m². The library area used for mass events must meet sanitary and hygienic requirements and have a separate entrance, lobby and toilets; a café or buffet can be located nearby.

The *recreation area* is allocated to provide refreshments and leisure activities for library visitors and users.

The *round-the-clock operations areas* are designed to provide access to library services at night time. The entrance to the premises is available from the side street (at night), as well as from inside of the library (during the day).

Studies of the range of services provided by the university library show that the availability of various functions of library premises has a positive effect on the psycho-emotional state of users. It helps to reduce the psychological load that comes from a long stay in a monotonous information space (especially when the types of activities and the nature of the environment do not change for a long time). Moreover, it increases library attendance, among other things.

That is why it is not the number of rooms and their name that is important, but – above all – the functional fullness, the idea of what should happen in them. The same space can perform different functions at different times, that is, it can be multifunctional. Therefore, it is important to determine for which activities it is intended and how many people will use it at the same time (Langie, Smiechowski, & Walczyna, 2012).

A vivid example of a well-thought-out functional and planned organisation of the social block in the structure of the library building is the National Technical Library in Prague. It is located in an open area surrounded by two universities, making students make a significant share of its visitors. The library has a conference hall, an exhibition hall, a cafeteria with 150 seats, a bookstore, a wardrobe and a self-service book return point. All these rooms are grouped around a huge hall, which serves as a meeting place not only for library users, but also for the general public. In addition, at the same level, there is a room for nighttime study that has a separate entrance from the side street (National Technical Library, 2009).

The **library block** (biblioblock) is an area of limited access to library premises and services. Access for users to the library block is possible only with a library card, entry is through a security gate, which is appropriately equipped. Access for personnel is ensured in the same way, subject to the availability of IDs (plastic cards).

Analysis of the floor plan of several libraries highlighted the main functional elements of the library space: a book distribution, a subscription area, a catalogue (card and electronic), a reading room, a book depository and administrative/operations premises. (Fig. 2).

The book distribution area is a point of handing out pre-ordered book items to be used in the reading room or in other rooms of the library.

A *subscription area* is a point for handing out pre-ordered book items to be used outside the library. Since there is a risk of increased noise during the most crowded periods, it is advisable to arrange it separately from the reading room. For ease of use, the subscription area must be placed directly at the entrance to the library or near the main communication routes (lifts, stairs, ramps).

A *card catalogue* is a way of registering existing library stock using bibliographic cards that are fixed and stored in the drawers of catalogue cabinets. The traditional card catalogue is typically located in

separate rooms, near the book distribution point and the reading room. In libraries with decentralised book distribution and a decentralised book depository, there is a need to arrange a dedicated card catalogue in each library section.

The *electronic catalogue* is a form of registration of the existing library collection in electronic form, placed in the library's virtual environment. To set up electronic catalogue, you do not need to allocate separate premises – it would be enough to equip a certain number of automated workstations in the most popular areas of the library.

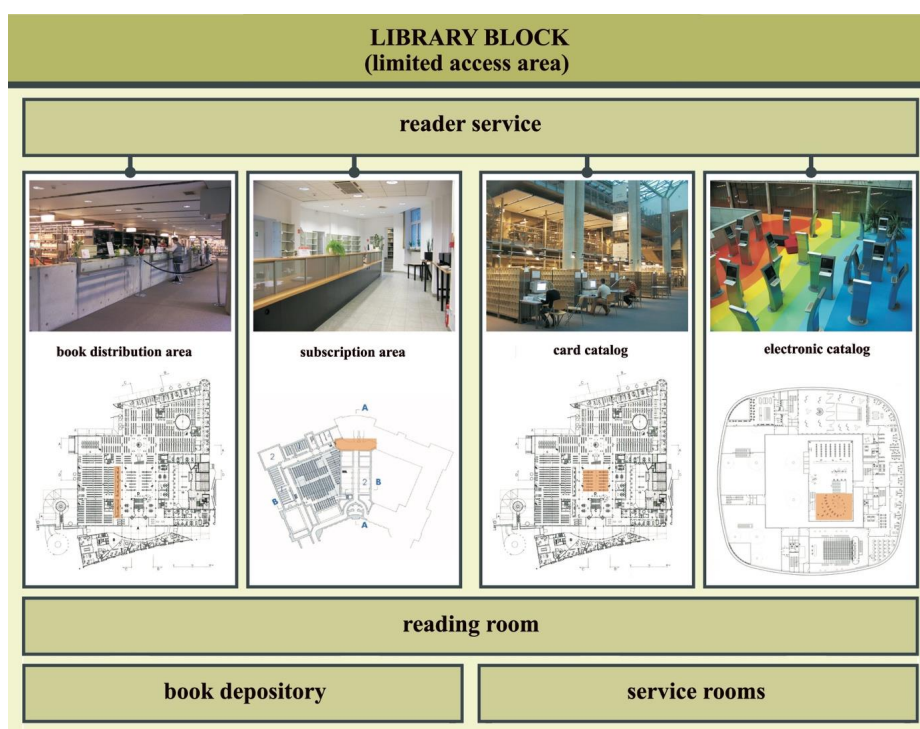


Fig. 2. Functional and planning elements of the library block

Source: own work.

A *reading room* is a room or part of a library space and is equipped with stations for working with information on various types of media (Fig. 3).

The following reading rooms are distinguished:

- General reading room: the main room in the structure of any library designed for familiarisation with general scientific literature; it can be single-level or multi-level and is often equipped with its own book distribution department.
- Sectoral reading room: a room for the study of specialised literature. It is often a separate structural unit of the library with its own book collection. A library located in a separate building may have in its structure several reading rooms with books devoted to a particular field and related sciences.
- Periodical literature reading room: rooms for processing periodicals. It may be accommodated in a separate hall in the general structure of the library or in a separate area of the main reading room. Shelves with periodicals are usually placed directly in the hall, except for large-format periodicals (newspapers, magazines, illustrations) or especially valuable publications.

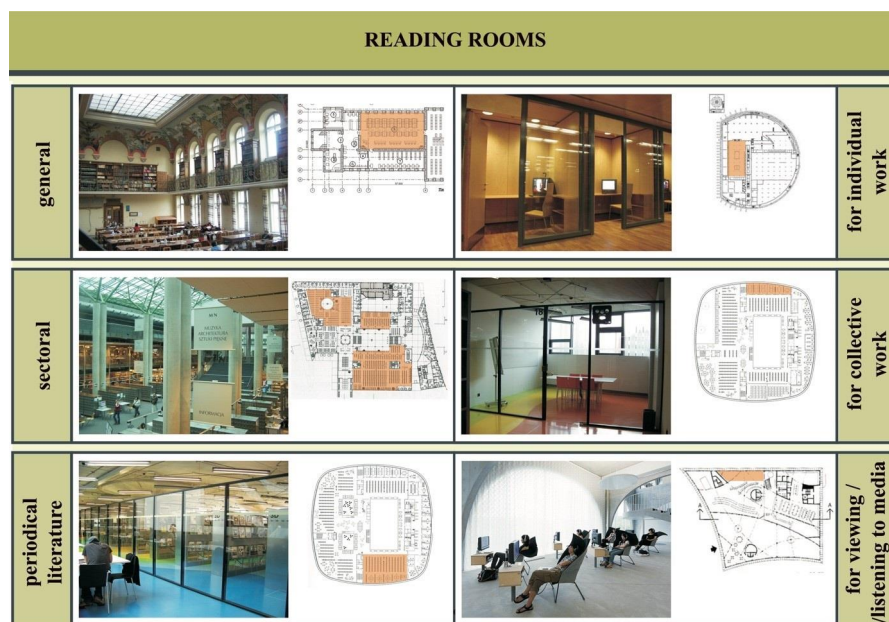


Fig. 3. Types of reading rooms

Source: own work.

- A room with seats for individual work: a space equipped for an individual to work conveniently and efficiently. The most common form of organisation of a place for individual work is a personal cabin (about 1.5×2.0 m), in the shape of a separate cell.
- A room with places for collective work: a space equipped with everything necessary for convenient and high-quality use by a different number of people. To avoid the spread of noise generated during collective work, the group space shall be separated from the reading room by partitions (in modern libraries, translucent partitions are used).
- A room for viewing/listening to media files: a space equipped with appropriate technical means. It can be in the form of separate special rooms in the structure of the library, or a dedicated area within the library hall or general reading room.

The number of seats in the library reading rooms is calculated as a proportion of the total number of readers. The standard for providing reading places in libraries of higher educational institutions is 12% of the number of full-time students (Paperno, 1969).

A *book depository* is a room with special humidity and temperature control equipment that should optimally meet the fire safety requirements, have dust level sensors and microorganisms protection means, etc. (Fig. 4).

The space-planning solutions for the structure of book depositories that largely determine the composition of any library include three main types: underground, ground-level and combined.

Underground book depositories are used to store large volumes of library stock (more than 1 million items in collections). Library users do not have access to them. There are single-level and multi-level underground book depositories. Ground-level book depositories are used to store library collections of any size. They can be either closed or open for free access to library users. There are single-level and multi-level ground-based book depositories. Combined book depositories are utilised to store large and extra-large volumes of library holdings, some of which are open to free access by library users. Combined book depositories are primarily multi-level.

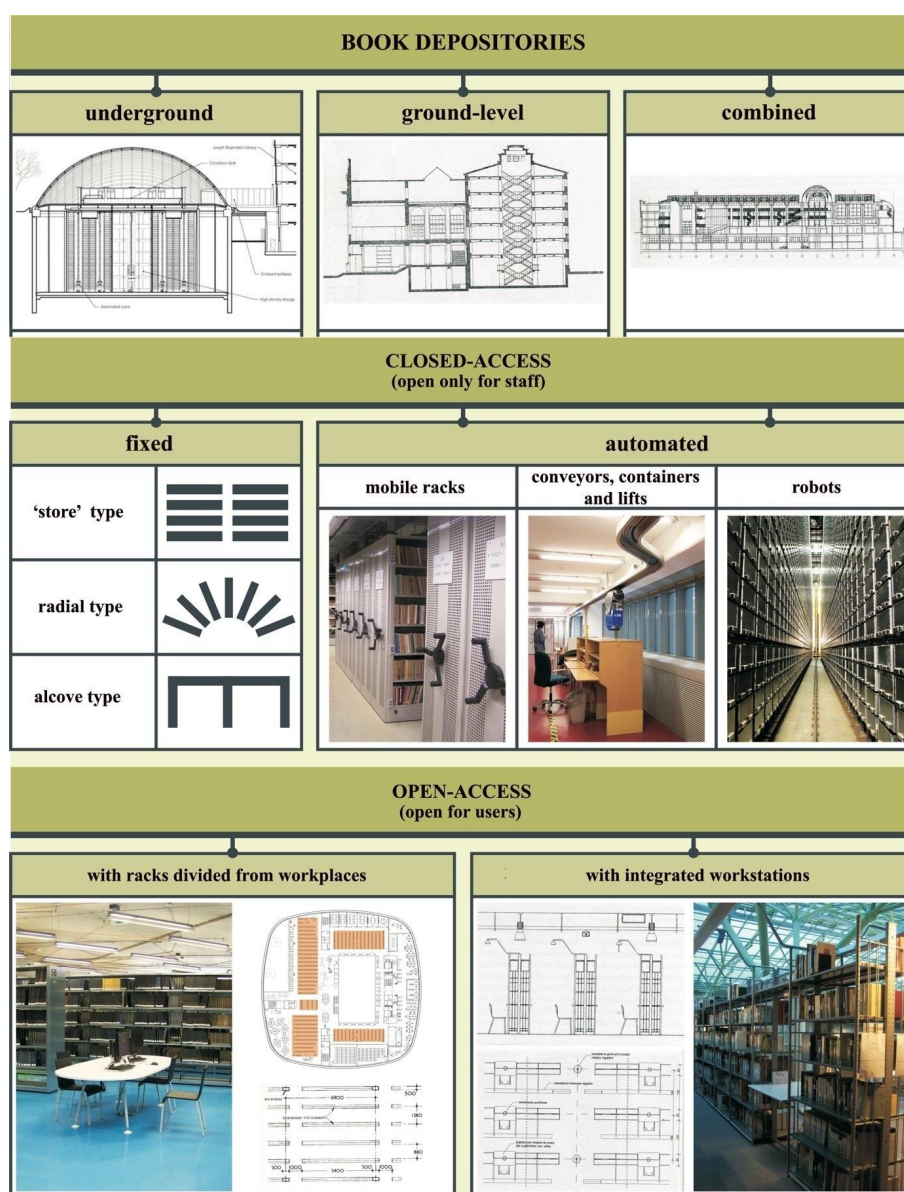


Fig. 4. Types of book depositories

Source: own work.

According to the method of accessing the book depository holdings, there are two-types: closed-access and open-access types. Only library staff are permitted to enter the closed-access book depository, while the open-access book depository provides free access to all users.

Closed-access book depositories include fixed and automated book depositories. In fixed book depositories, the library holding is located on fixed racks in the appropriate order. There are three types of rack placement:

- ‘Store’ type: orderly placement of book racks following the principle of parallel rows. Racks and structural elements are separated by aisles, the smallest width of which is 0.75 m between the racks; 1.2 m between the ends of the racks, 0.75 m between the wall and the rack parallel to the wall and 0.45 m between the wall

and the end of the rack. Book depositories of the ‘store’ type are single-tiered or multi-tiered. In multi-tiered ground-based book depositories, in addition to side natural lighting, light lamps are often arranged, and metal ceilings with a lumen are also used to better illuminate the lower tiers (Voronkova, 2016).

- Radial type: a system of flexible placement of racks in a circle, the centre of which is the department of book distribution. This principle of placing shelves in book depositories has not become widespread, due to the complex organisation of internal itineraries for handing out books. It is mostly used in reading rooms with open access to racks.
- Alcove type: a system of U-shaped placement of book racks, where one rack is located along the wall, and the other two are perpendicular. Inside the resulting space, reading desks (or tables) are placed, which are used to view the ordered book items. This principle of rack placement is typical for libraries with open access to racks.

Automated book depositories are equipped with equipment to speed up the process of finding and providing a book to the reader. There are three types of technical equipment:

- Mobile racks: movable storage systems that move easily, match with each other and open in the right places. They are designed to minimise the needed space and optimise access to stored materials. There are mechanical and electronic racks.
- Conveyors, containers and lifts: technical equipment designed to transport materials ordered by the user to the distribution point. Conveyors and containers are used for vertical and horizontal transportation, lifts are meant only for vertical delivery of books.
- Robots: a system for the search and delivery of materials based on the use of radio frequency identification marks (RFID). It is used in modern book depositories.

One of the most interesting examples of an automated underground book depository is the University of Chicago Library. Each copy of a book in the library is equipped with a unique RFID chip that contains specific information about it. When you borrow or return a book, the chip is scanned and changes are automatically entered into the database. The library stock is stored in special three-tier racks, and robots are used to search for and deliver books to the RFID scanner. The average search time for five books is about 2.5 min (Voronkova, 2012).

Open-access book depositories can be of two types:

- with racks divided from workplaces: racks are placed around work desks, creating a closed space for individual work; in open access, the passage between the racks is recommended to be at least 1 m;
- with integrated workstations: desks are placed directly within the space of the book rack.

Service rooms include premises for the compilation and processing of book stock, research departments, service catalogues, administrative and economic sections, and auxiliary premises (Fig. 5). At the same time, it is necessary to provide several staff entrances in the library, for example, for loading and unloading documents, for library staff, for supplying products to the buffet or dining room, etc. (Aleshin, 2008).

The office premises include administrative sections, office rooms, a recreation area, a staff kitchen, and special-purpose rooms.

Administrative premises include a director’s office, a meeting room, secretariat, registry department, an accounts department and an administrative and economic department. The number of administrative premises and their designations depend on the size of the library and the number of administrative staff, as well as their positions and functions.

Service rooms are the rooms where the main work processes take place to ensure the functioning of the library. The area of the rooms is determined by the standards per employee: 5–6 m² per person in a room for three staff members and 4.0–4.5 m² per person for a room to fit more employees (Pashchenko, 1941).



Fig. 5. Types of service rooms

Source: own work.

The recreation room or area is designed to relieve fatigue, visual tension and emotional stress of library staff. In large libraries, lounges should be located in the appropriate units; in small libraries, one common room is sufficient.

A staff kitchen is provided for refreshments and food consumption. For 6–10 library employees, a room with an area of 12 m² shall be allocated, and 2 m² shall be designed to fit kitchen equipment.

Special premises include: a restoration workshop, a bookbinding room, a disinfection room, printing house, a photo cabinet and a carpentry workshop. The availability of special premises depends on the size of the library and its functional purpose.

Typically, parameters for the required area for librarians' workplaces are obtained through analytical and synthetic methods that account for the peculiarities of library work in different processes and differentiate the required working areas for librarians, administrative staff, technical workers and managers.

In the libraries of the 21st century, there is a tendency to integrate various production processes into the traditional learning process. There are spaces for collective learning such as group study rooms, photography and video workshops, a 3D printing workshop, rehearsal and game rooms, a music recording studio and a model workshop (Sirel, 2021). The introduction of the latest technologies and updated spaces expands the boundaries of the classical library's functioning and enhances its important educational role in society. This directly affects the quality of education, diversifying and improving its traditional methods.

The real challenge for libraries in the 21st century was the COVID-19 pandemic. Even before the pandemic, libraries began to transition from physical to digital collections and services. Thus, in developed countries, educational institutions and libraries that serve them switched to a remote mode of operation during the epidemic. However, in underdeveloped countries, where access to the internet is often absent and the digitisation of the library collection is slow, the educational process took place in a hybrid form (Rafiq, Batool, Farzand Ali & Ullah, 2021).

Another important element to consider when creating a comfortable environment in various library rooms and spaces is light. Both natural and artificial lighting are actively used in library buildings. However, the specifics of the functional and planning organisation of libraries and the wide use of glass in library architecture require the architect to pay special attention to the use of natural lighting (Voronkova & Podlasek, 2024).

CONCLUSIONS

When designing and constructing university libraries, it is critical to take a thoughtful approach to their functional and planning organisation to facilitate their transformation into a multifunctional units. A modern university library is no longer a place for the accumulation and storage of printed materials. It is now an open and accessible public space with a flexible layout designed to meet the varying needs and functions of library users. The library of the 21st century creates a special psychological environment, fostering an atmosphere of hospitality and friendliness. It demonstrates an interest in the needs of each visitor and utilises a variety of ‘non-verbal’ means of communication, such as design, space organisation and colour solutions. These aspects help to overcome the barrier of alienation between visitors and the ‘official institution’. At the same time, changing functions in various library premises and spaces significantly reduce the psychological burden experienced by individuals when staying in a monotonous information environment.

The powerful development of information and communication technologies and their active implementation in daily library processes have changed the way information is stored. The traditional printed copy has received its digitised counterpart. Instead of disappearing as a physical institution by going digital, the library has taken on a new meaning by combining classic teaching and research models with new user-centred services.

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SPECYFIKA ORGANIZACJI FUNKCJONALNEJ I PRZESTRZENNEJ BIBLIOTEK UNIWERSYTECKICH

STRESZCZENIE

Biblioteka uniwersytecka to przestrzeń, w której zachodzą złożone procesy organizacyjne, przeplatają się różne obszary funkcjonalne i współistnieją odrębne harmonogramy ruchu. Jeśli fizyczna przestrzeń biblioteki nie zapewnia wysokiej jakości warunków pracy indywidualnej i grupowej, szybkiego i swobodnego dostępu do zasobów informacyjnych, możliwości korzystania z komputera i ze sprzętu kopiującego itp., to taki obiekt nie będzie odwiedzany zbyt często. Wszystko to determinuje specyfikę organizacji wewnętrznej przestrzeni biblioteki. W celu ustalenia tego należy ponownie przeanalizować strukturę przestrzenną biblioteki z punktu widzenia możliwego rozwoju funkcjonalnego. Z tego powodu celem artykułu jest podkreślenie głównych elementów funkcjonalnych i przestrzennych współczesnej biblioteki, których obecność lub brak bezpośrednio wpływa na jakość jej funkcjonowania.

Słowa kluczowe: biblioteka uniwersytecka, organizacja planowania funkcjonalnego, czytelnia, magazyn książek, pokój obsługi

THE INFLUENCE OF MICROSTRUCTURE SIZE ON TEMPERATURE DISTRIBUTION IN BIPERIODIC COMPOSITE

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ABSTRACT

In this work, the problem of heat conduction in a biperiodic composite consisting of two constituent materials was analysed. To average the discontinuous coefficients in the heat conduction equation, which arise from the heterogeneous structure, the technique of tolerance modelling was applied. The finite difference method was then used to solve the resulting system of equations and to determine the distribution of the unknowns. The finite difference method algorithm was implemented in Maple 2019 software. The main objective of the analysis was to investigate the influence of the composite's microstructure size on the distribution of the unknowns, facilitated by the tolerance model equations derived through the tolerance modelling technique. The study demonstrated how the number of composite cells, and consequently the cell size, affects temperature values and their fluctuations under selected boundary conditions.

Keywords: heat conduction, composites, biperiodicity, tolerance modelling

INTRODUCTION

Composites are structures composed of two or more materials. The design of such structures aims to create materials that exhibit better properties than homogeneous materials. Composites can feature improved mechanical strength, hardness, as well as lower weight or better thermal conductivity than homogeneous structures. Composite structures are widely used across various industries due to their enhanced properties compared to traditional materials. In the aerospace industry, composites are used to manufacture lightweight yet strong components, such as aircraft fuselages, wings and engine parts, which contribute to fuel efficiency. In the automotive sector, they are employed in the production of car bodies, chassis and interior components, thereby reducing vehicle weight. In the construction industry, composites are utilised for building materials, offering durability and resistance to environmental factors. The marine industry benefits from composites in the construction of hulls and other structural parts of boats and ships, providing resistance to corrosion and reduced maintenance costs. Composites are also used in the sporting goods industry to create high-performance equipment such as tennis rackets, golf clubs and bicycles, where strength, stiffness, and lightweight are essential. Additionally, in the energy sector, composites are integral to the manufacturing of wind turbine blades and other renewable energy infrastructure, where their strength and lightness enhance efficiency and longevity.

Therefore, it is crucial to understand the methods that allow for the examination and analysis of heterogeneous structures, among which periodic and biperiodic structures can be distinguished. Among such methods, asymptotic homogenisation (Bensoussan, Lions & Papanicolay, 1978), a certain variant of

homogenisation that introduces the concept of microlocal parameters (Matysiak & Nagórko, 1989), the finite element method (Santos, Mota Soares, Mota Soares & Reddy, 2008), the higher order theory (Aboudi, Pindera & Arnold, 1999) and tolerance modelling (Woźniak, Michalak & Jędrzyśiak, 2008) should be mentioned.

In the case of periodic or biperiodic structures with a repetitive (recurrent) pattern, it is possible to mentally isolate repeatable cells that have the same structure. The microstructure parameter is then defined as the dimension of such a cell for periodic structures, or as the two dimensions along two perpendicular axes of the coordinate system for biperiodic structures. Not all of the mentioned methods take into account the influence of the size of the microstructure parameter in the issues considered. Therefore, this work employs tolerance modelling, which allows for the consideration of this influence. This technique, by introducing a series of new concepts and assumptions, enables the averaging of equations where the coefficients are discontinuous and highly oscillating. Tolerance modelling is used in the analysis of heat conduction (Kubacka & Ostrowski, 2021; Ostrowski & Jędrzyśiak, 2021), thermoelasticity (Kubacka & Jędrzyśiak, 2018; Tomczyk, Gołąbczak & Gołąbczak, 2024), dynamics (Domagalski, 2018; Tomczyk, Gołąbczak, Litawska & Gołąbczak, 2023) and stability problems (Marczak & Jędrzyśiak, 2021; Tomczyk, Bagdasaryan, Gołąbczak & Litawska, 2021).

The problem analysed in this work is the heat conduction issue in a biperiodic composite, made of two different materials. The equations describing it were averaged using tolerance modelling, and their numerical solution was then obtained using the finite difference method. The finite difference method algorithm was implemented in the Maple 2019 software. This algorithm enabled the calculation and presentation of the temperature distribution in the analysed structure under the assumed boundary conditions. Additionally, the influence of the volume fractions of the individual materials within the cell on the temperature distribution throughout the entire composite was examined. The volume fraction of the individual materials affects not only the thermal properties of the structure but also its weight, mechanical strength and production cost.

OBJECT UNDER CONSIDERATION

Figure 1 shows the analysed composite, consisting of two different constituent components. The dimensions of the composite are denoted by L_x along the x-axis and L_y along the y-axis. The microstructure parameter (mentally isolated cell dimension) along the x-axis is denoted by l_x and along the y-axis is denoted by l_y and it is dependent on the number of cells (N) in the entire structure.

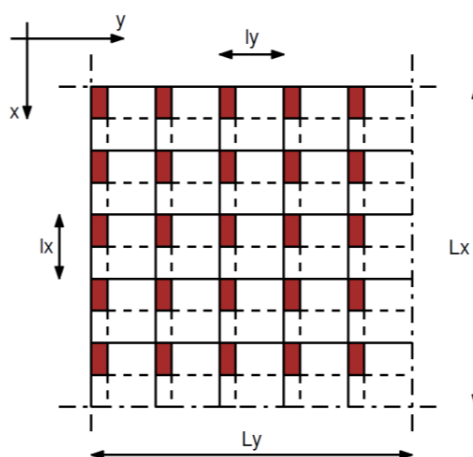


Fig. 1. Composite with biperiodic structure

Source: own work.

The volume fraction of the first and second material within the cell is constant. In the conducted analysis, the number of cells (N) is variable and, consequently, the dimension of the microstructure parameters are also variable.

In relation to the considered structure, the heat conduction problem was analysed and described by following Fourier equation:

$$\partial_i (\mathbf{K}_{ij} \partial_j \theta) - c \rho \dot{\theta} = 0, \quad (1)$$

where:

$\mathbf{K}_{ij}$ – tensor of conductivity,

θ – total temperature field,

c – specific heat,

ρ – mass density,

i, j – indices equal to 1, 2, 3.

The material coefficients in Eq. 1 are discontinuous due to the heterogeneous structure of the composite.

TOLERANCE MODELLING

Tolerance modelling is a technique initiated by Professor Czesław Woźniak and later continued and developed in many research institutes (Tomczyk, Gołabczak, Kubacka, Bagdasaryan, 2024). In addition to allowing for the consideration of the influence of microstructure size in the analysed problems, this technique does not require solving the problem at the cell level to determine appropriate shape functions – unlike asymptotic homogenisation.

This technique introduces a series of new concepts, the most significant of which, in the context of the conducted research, are the tolerance-periodic function, the slowly varying function and the highly oscillating function.

A function f can be described as tolerance-periodic (with respect to the primary cell Δ and the tolerance parameter δ) if it satisfies the following conditions:

$$(\forall x \in \Omega) (\exists \tilde{f}^{(i)}(x, \cdot) \in H^0(\Delta)) \left(\left\| \partial^i f|_{\Omega_x}(\cdot) - \tilde{f}^{(i)}(x, \cdot) \right\|_{H^0(\Omega_x)} \leq \delta \right), \quad (2)$$

$$\int_{\Delta(\cdot)} \tilde{f}^{(i)}(\cdot, z) dz \in C^0(\overline{\Omega}), \quad (3)$$

where:

$\partial^i f$ – gradient of order i function f ,

$\tilde{f}(x, \cdot)$ with $\sim$ – periodic approximation of the gradient $\partial^i f$,

Ω – region bounded in R^2 ,

Ω_x – cluster of adjacent cells,

Δ – primary cell,

$H^0(\Delta)$ – area of Δ -periodic square-integrable functions defined in R^2 ,

$H^0(\Omega_x)$ – area of Δ -periodic square-integrable functions defined in Ω_x ,

δ – tolerance parameter.

On the other hand, function u can be described as slowly varying (with respect to the primary cell Δ and the tolerance parameter δ) when it is a tolerance-periodic and it satisfies the following condition:

$$(\forall x \in \Omega) (\tilde{u}^{(i)}(x, \cdot)|_{\Delta(x)} = \partial^i u(x), i = 0, 1), \quad (4)$$

where:

$\Delta(x)$ – cell centred at the point x .

The function h can be described as highly oscillating (with respect to the primary cell Δ and the tolerance parameter δ) when it is a tolerance-periodic and it satisfies the following condition:

$$(\forall x \in \Omega) (\tilde{h}^{(i)}(x, \cdot)|_{\Delta(x)} = \partial^i \tilde{h}(x), i = 0, 1). \quad (5)$$

The main assumption of tolerance modelling is the assumption of so-called micro-macro decomposition of the temperature field (in the carried-out analysis). This assumption is described by the following equation:

$$\theta(x, y) = \vartheta(x, y) + g_a(x, y) \cdot \psi_a(x, y), \quad (6)$$

where:

θ – total temperature field,

ϑ – average temperature,

g_a – fluctuation shape functions,

ψ_a – fluctuation amplitudes,

a – index runs over 1 and 2.

The average temperature ϑ and fluctuation amplitudes ψ_a are new fundamental unknowns, while the fluctuation shape functions are taken based on literature and experience. The fluctuation shape functions g_1 and g_2 adopted in this problem are a combination of saw-type function and piecewise parabolic function (Fig. 2).

Symbols v_x and v_y represent the volume fraction of the first material in the cell along the x-axis and y-axis, respectively.

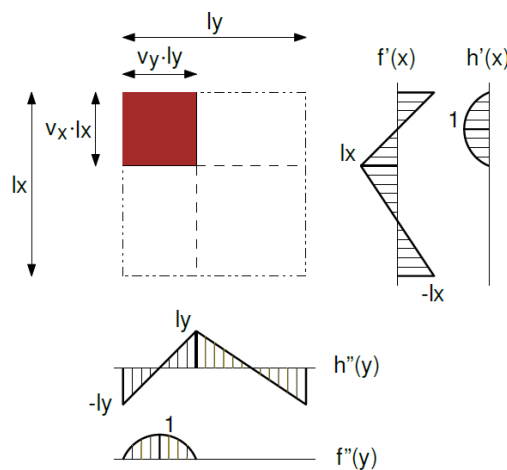


Fig. 2. Fluctuation shape functions

Source: own work.

The mentioned shape functions are expressed by the following equations:

$$g_1(x, y) = f'(x) \cdot f''(y), \quad (7)$$

$$g_2(x, y) = h'(x) \cdot h''(y). \quad (8)$$

Using the above concepts and assumptions, the equations of the tolerance model were derived, in which the coefficients are average and slowly varying. These equations include terms that directly depend on the dimension of the microstructure, as shown:

$$\langle c\rho \rangle \dot{\vartheta} + \langle c\rho g_1 \rangle \dot{\psi}_1 + \langle c\rho g_2 \rangle \dot{\psi}_2 - \nabla \cdot \left(\begin{aligned} &\langle \mathbf{K} \rangle \cdot \nabla \vartheta + \langle \mathbf{K} \cdot \partial g_1 \rangle \psi_1 + \langle \mathbf{K} g_1 \rangle \cdot \bar{\nabla} \psi_1 + \\ &+ \langle \mathbf{K} \cdot \partial g_2 \rangle \psi_2 + \langle \mathbf{K} g_2 \rangle \cdot \bar{\nabla} \psi_2 \end{aligned} \right) = 0, \quad (9)$$

$$\begin{aligned} &\langle c\rho g_1 \rangle \dot{\vartheta} + \langle c\rho g_1 g_1 \rangle \dot{\psi}_1 + \langle c\rho g_1 g_2 \rangle \dot{\psi}_2 + \langle \mathbf{K} \cdot \partial g_1 \rangle \cdot \nabla \vartheta + \langle \mathbf{K} \cdot \partial g_1 \partial g_1 \rangle \psi_1 + \langle \mathbf{K} \cdot \partial g_1 g_1 \rangle \cdot \bar{\nabla} \psi_1 + \\ &+ \langle \mathbf{K} \cdot \partial g_1 \partial g_2 \rangle \psi_2 + \langle \mathbf{K} \cdot \partial g_1 g_2 \rangle \cdot \bar{\nabla} \psi_2 - \bar{\nabla} \cdot \left(\begin{aligned} &\langle \mathbf{K} g_1 \rangle \cdot \nabla \vartheta + \langle \mathbf{K} \cdot \partial g_1 g_1 \rangle \psi_1 + \langle \mathbf{K} g_1 g_1 \rangle \cdot \bar{\nabla} \psi_1 + \\ &+ \langle \mathbf{K} \cdot \partial g_2 g_1 \rangle \psi_2 + \langle \mathbf{K} g_1 g_2 \rangle \cdot \bar{\nabla} \psi_2 \end{aligned} \right) = 0, \end{aligned} \quad (10)$$

$$\begin{aligned} &\langle c\rho g_2 \rangle \dot{\vartheta} + \langle c\rho g_2 g_1 \rangle \dot{\psi}_1 + \langle c\rho g_2 g_2 \rangle \dot{\psi}_2 + \langle \mathbf{K} \cdot \partial g_2 \rangle \cdot \nabla \vartheta + \langle \mathbf{K} \cdot \partial g_2 \partial g_2 \rangle \psi_1 + \langle \mathbf{K} \cdot \partial g_2 g_1 \rangle \cdot \bar{\nabla} \psi_1 + \\ &+ \langle \mathbf{K} \cdot \partial g_2 \partial g_2 \rangle \psi_2 + \langle \mathbf{K} \cdot \partial g_2 g_2 \rangle \cdot \bar{\nabla} \psi_2 - \bar{\nabla} \cdot \left(\begin{aligned} &\langle \mathbf{K} g_2 \rangle \cdot \nabla \vartheta + \langle \mathbf{K} \cdot \partial g_1 g_2 \rangle \psi_1 + \langle \mathbf{K} g_1 g_2 \rangle \cdot \bar{\nabla} \psi_1 + \\ &+ \langle \mathbf{K} \cdot \partial g_2 g_2 \rangle \psi_2 + \langle \mathbf{K} g_2 g_2 \rangle \cdot \bar{\nabla} \psi_2 \end{aligned} \right) = 0, \end{aligned} \quad (11)$$

where:

∇ – gradient in x-, y- and z-directions,

overlined ∇ – gradient in z-direction,

∂ – gradient in x- and y-directions.

FINITE DIFFERENCE METHOD ALGORITHM

To find the numerical solution of the tolerance model equations (Eqs 9–11), the finite difference method was chosen. The idea of this method is to replace the set of admissible solutions with a set of function values at points within the region, subject to appropriate discretisation and to replace the function derivatives at those points with the corresponding finite difference quotients defined at those points. For this purpose, the composite area was discretised in both directions (Fig. 3). Along the x-axis, it was divided into segments Δx of equal length, introducing $m + 1$ nodes, with Δx equal to $Lx \cdot m^{-1}$. Along the y-axis, it was divided into segments Δy of equal length, introducing $n + 1$ nodes, with Δy equal to $Ly \cdot n^{-1}$.

The concept of the finite difference method allows for the replacement of a system of differential equations with a system of linear algebraic equations, written at each node of the discretised region, where the unknown values of the average temperature and fluctuation amplitudes – those not specified by boundary conditions – are sought.

As mentioned, the equations are written only at the nodes where the unknowns are not defined. Unfortunately, in the analysed problem, there are three unknowns for which different boundary conditions are specified (at different nodes). Additionally, the equations written at the boundary and near-boundary nodes lead to the emergence of unknowns defined at nodes outside the composite region – so-called virtual nodes. Subsequently, the unknowns at the virtual nodes are eliminated from the equations using the boundary conditions.

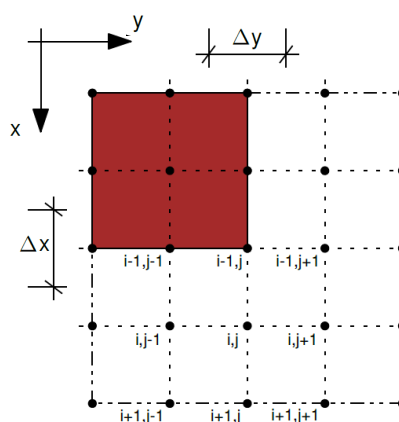


Fig. 3. Discretised area

Source: own work.

To create an algorithm in Maple 2019 software, the coefficients associated with the unknowns in all equations were grouped and ordered, forming a global coefficient matrix. Similarly, the components of the free term vector, resulting from the boundary conditions and known values of the unknowns at selected nodes, were grouped. The system of algebraic equations was then solved, yielding the numerical solution and the distribution of the sought unknowns.

EXAMPLE OF APPLICATION

The finite difference method algorithm was used to investigate the influence of microstructure size on the heat conduction analysis in a biperiodic composite with dimensions $L_x = L_y = 1$ m. It was assumed that the composite consists of two components, for which material properties such as specific heat, mass density and thermal conductivity coefficients were defined, similar to those of steel and aluminium (Fig. 4).

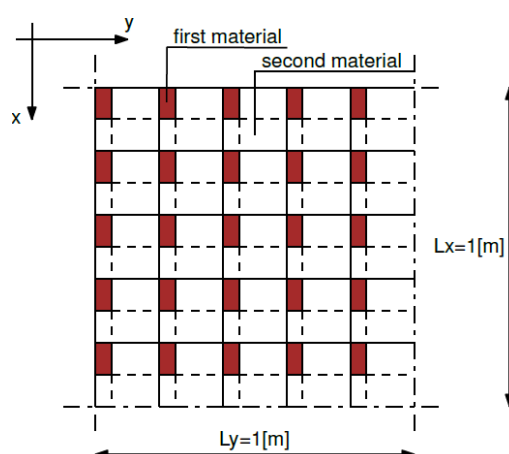


Fig. 4. Considered biperiodic composite

Source: own work.

The volume fraction of the first material in the cell was set to 0.5 along the x-axis and 0.25 along the y-axis. In the initial analysis, it was assumed that the composite consisted of $N = 10$ repeating cells along both axes of the coordinate system. Subsequently, the necessary initial boundary conditions were applied.

For the problem under consideration, the following boundary conditions were assumed: with respect to the average temperature ϑ (Fig. 5a), it was assumed that its values were known on the left and top edges of the composite (Area 1), while the right and bottom edges were thermally insulated (Area 2). With respect to the fluctuation amplitudes of the temperatures ψ_1 and ψ_2 (Fig. 5b), it was assumed that its values were known on all edges (Area 1). An initial condition was also specified in the form of known averaged temperature and fluctuation amplitudes of the temperatures during the first-time step.

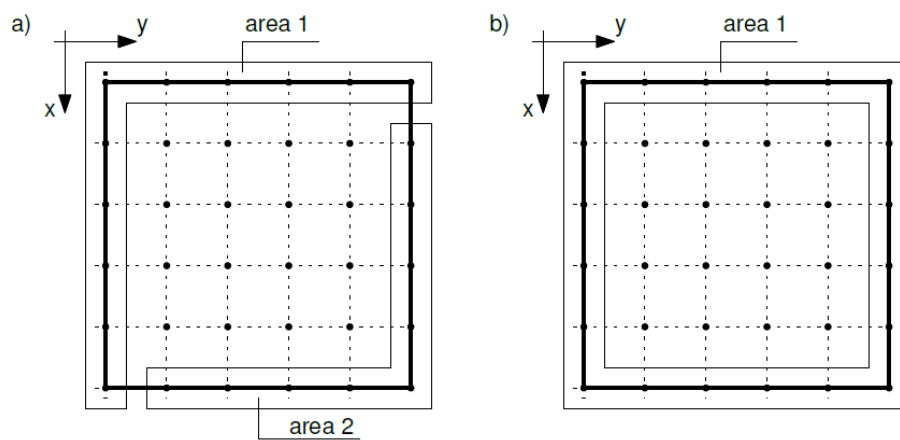


Fig. 5. Areas of defined boundary conditions

Source: own work.

The results of the initial analysis, in the form of 3D maps of the sought dimensionless unknowns (approximated) in the final time step, are shown in Figures 6–8.

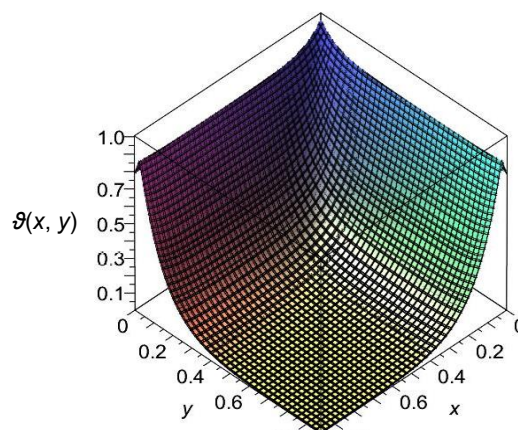


Fig. 6. Average temperature ϑ – initial analysis

Source: own work.

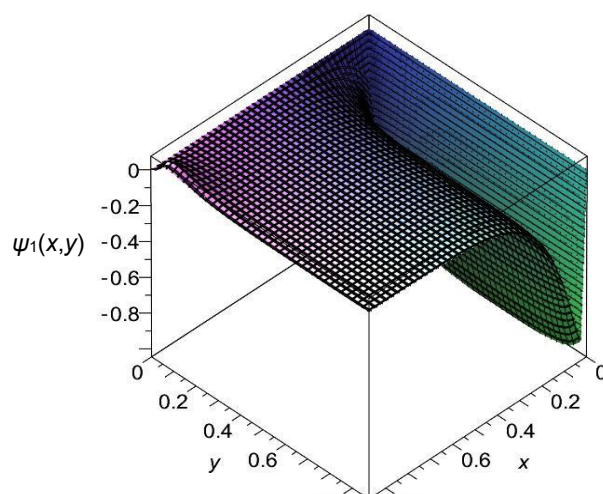


Fig. 7. Fluctuation amplitudes of the temperature ψ_1 – initial analysis

Source: own work.

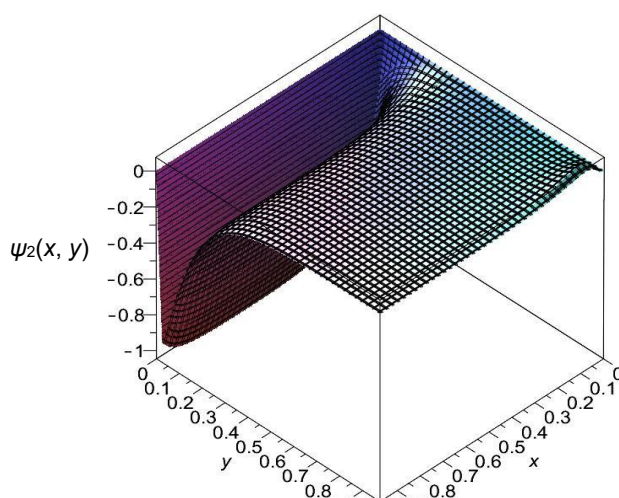


Fig. 8. Fluctuation amplitudes of the temperature ψ_2 – initial analysis

Source: own work.

The calculations were then repeated, increasing the number of cells to $N = 20$ and $N = 30$, thereby changing the dimension of the microstructure parameter.

The comparison of the average temperature distribution and the temperature fluctuation amplitudes in a selected cross-section ($x = 0.5Lx$) for different numbers of cells is presented in Figures 9–11.

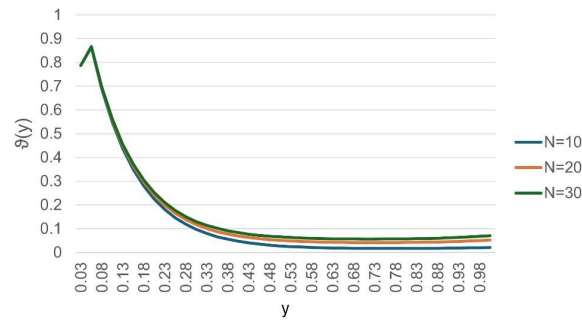


Fig. 9. Comparison of macrotemperature ϑ distribution for different numbers of cells

Source: own work.

Increasing the number of cells, and consequently reducing the microstructure size, led to an increase in the average temperature values, with relative differences (compared to the higher value) reaching up to 70.6%.

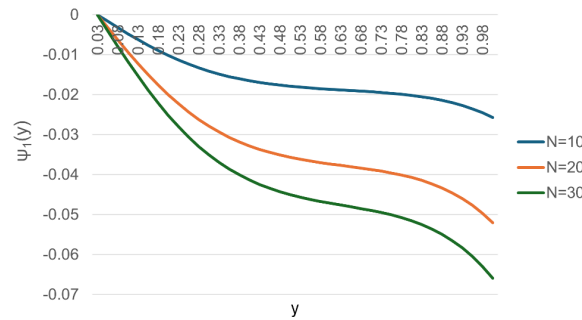


Fig. 10. Comparison of fluctuation amplitudes ψ_1 distribution for different numbers of cells

Source: own work.

A similar relation was observed in the case of fluctuation amplitudes of the temperature ψ_1 , with relative differences (compared to the higher value) ranging from 49.2% to 61.1%.

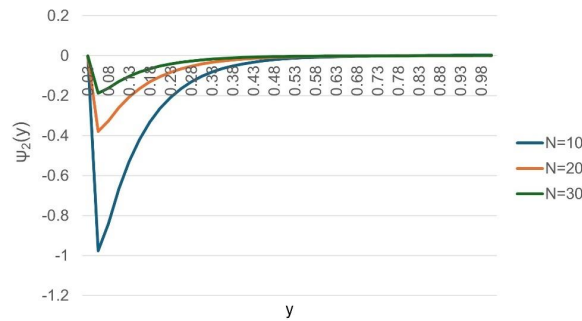


Fig. 11. Comparison of fluctuation amplitudes ψ_2 distribution for different numbers of cells

Source: own work.

An opposite relation was observed in the case of fluctuation amplitudes of the temperature ψ_2 – as the number of cells increased, meaning the microstructure parameter size reduced, the amplitude values decreased with relative differences (compared to the higher value) ranging from 40.1% to 139.5%.

SUMMARY AND CONCLUSIONS

Based on the conducted analysis, the following general and specific conclusions were formulated:

1. Tolerance modelling enables the replacement of differential equations with tolerance-periodic, discontinuous and highly oscillating coefficients, with a system of equations that have slowly varying coefficients.
2. The obtained tolerance model equations allow for the consideration of the influence of microstructure size in the analysed problems.
3. The tolerance modelling technique does not require solving the problem at the cell level to find the fluctuation shape functions.
4. The created finite difference method algorithm allows for obtaining the temperature distribution in the analysed structure, which enables a better understanding of the behaviour of composites under thermal load.
5. The analysis shows the significant impact of the number of composite cells on the average temperature and fluctuation amplitudes distribution, as it directly affects the cell dimension, which corresponds to the microstructure size.

Authors' contributions

Conceptualisation: E.K. and P.O.; methodology: E.K. and P.O.; validation: E.K.; formal analysis: E.K.; investigation: P.O.; resources: E.K.; data curation: P.O.; writing – original draft preparation: E.K.; writing – review and editing: E.K. and P.O.; visualisation: E.K.; supervision: P.O.; project administration: P.O.

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

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WPŁYW WYMIARU MIKROSTRUKTURY NA ROZKŁAD TEMPERATURY W BIPERIODYCZNYM KOMPOZYCIE

STRESZCZENIE

W niniejszej pracy przeanalizowano zagadnienie przewodzenia ciepła w biperiodycznym kompozycie składającym się z dwóch materiałów składowych. W celu uśrednienia nieciągłych współczynników w równaniu przewodzenia ciepła, wynikających z niejednorodnej budowy struktury, zastosowano technikę tolerancyjnego modelowania. Następnie wykorzystano metodę różnic skończonych do rozwiązania otrzymanego układu równań i znalezienia rozkładu poszukiwanych niewiadomych. Algorytm metody różnic skończonych zaimplementowano w programie Maple 2019. Głównym celem przeprowadzonej analizy było zbadanie wpływu wymiaru mikrostruktury kompozytu na rozkład poszukiwanych niewiadomych, co umożliwiły równania modelu tolerancyjnego otrzymane dzięki wykorzystaniu techniki tolerancyjnego modelowania. W pracy pokazano, w jaki sposób liczba komórek kompozytu (a co za tym idzie wymiar komórki) wpływa na wartości temperatury i jej fluktuacji w wybranych warunkach brzegowych.

Słowa kluczowe: przewodzenie ciepła, kompozyty, biperiodyka, tolerancyjne modelowanie

INCREASING THE DURABILITY OF LARGE-CALIBRE CANNON BARRELS THROUGH STRENGTHENING THEM BY SURFACE PLASTIC DEFORMATION

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ABSTRACT

The paper presents a technology for strengthening the internal surface of the bore of cannon and tank barrels through surface plastic deformation. It is recommended to carry out the strengthening treatment in two stages: firstly, ball peening of the inner working surface of the barrel with hardened steel balls; secondly, application of a heat-resistant hard alloy coating using deforming bodies made of the VK6 alloy. It was established that as a result of this strengthening treatment, residual compressive stresses are formed in the near-surface layer of the bore material, its surface microhardness increases and the resistance of the metal in the working surface of the barrel against burnout and cracking improves. Overall, the resistance of the barrel material to wear during cannon shots increases. A design of the strengthening device for this treatment has been developed. It consists of a cylindrical hardener with deforming bodies, an electric drive motor and a torque transmission mechanism from the motor shaft to the hardener. During the strengthening treatment, the device is moved along the channel of the cannon barrel, allowing the hardener to roll over the processed inner surface of the barrel andpeen its material. The provided strengthening thickness is 0.15–0.20 mm, while the thickness of the applied hard alloy coating is up to a 100 µm.

Keywords: cannon barrel, hard alloy, coating, wear, surface strengthening, ball peening

INTRODUCTION

During each shot of the cannon, the internal surface layers of its barrel channel are exposed to the active destructive influence of high temperatures (up to 1,000°C), the chemical action of powder gases, extremely high pressures and mechanical wear from the movement of a projectile along the barrel. This leads to the destruction of the structure, a decrease in the strength and density of the metal surface layers, its burning and wear, which ultimately results in a violation of the geometry of the working surface of the bore. The violation of the geometry of the working surface of the cannon barrel channel negatively affects the range and, most importantly, the accuracy of aiming and other accuracy-related tactical and technical characteristics

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of the cannon. The excessively worn inner working surface of the bore is almost impossible to repair and restore. As a result, each cannon is characterised by a permissible number of aimed shots, which – to some extent – limits the duration of the effective use of cannons.

The analysis of the technological processes of forming monoblock cannon barrels and liners (replaceable pipes) of multilayer barrels, as well as the technological operations of their further mechanical processing, proves that all of them ultimately form tensile stresses along the radial direction of the surface layers of the barrel material. High-temperature heating during shots, accompanied by pressures up to several thousand atmospheres, also tend to break the barrel and attempts to increase its diameter. Then, operational loads additionally form operational tensile stresses in the near-surface layers of the material. In total, technological and operational tensile stresses reach a fairly high gradient. The induced stresses tend to break intermolecular bonds of the material on the surface of the borehole, forming microcracks in the near-surface layer of the metal. As a result, microscopic pieces of metal peel off from the working surface of the barrel and burn in the flame and high-temperature powder gases. Due to this, the geometry of the barrel bore is disturbed, and the accuracy of aimed shooting deteriorates.

Taking this into account, designers and developers are striving to improve the operational properties of parts and assemblies through technological methods (Shyrovkov, Kusi, Aftanaziv, Borovets & Kuk, 2010; Kusi & Kuk, 2015). This is achieved by the technologically enhancing the characteristics of the most heavily loaded surface layers of the material of the parts, particularly their roughness and surface microhardness, in order to establish a material stress state which would be capable of withstanding operational loads (Kusi & Topilnytskyi, 2009; 2013). Shyrovkov et al. (2010) investigated the potential for increasing the wear resistance of the inner surface of drill pump sleeves through strengthening by surface plastic deformation. This resulted in an over 25% increase in the wear resistance of the pump material. However, abrasive wear is not typical for cannon bores. Therefore, the results of these studies cannot be applied without proper refinement to enhance the durability of cannon barrels.

The resistance of the barrel material to operational wear could be significantly increased by incorporating strengthening operations into the manufacturing process of cannon barrels, which would ensure the formation of compressive stresses in the outer layers of the barrel material (Aftanaziv & Shevchuk, 2018a; 2018b; 2018c).

The purpose of the research is the development of technology for strengthening internal channels of large-calibre cannon barrels by surface plastic deformation to increase their strength characteristics, reliability and durability. In order to achieve this goal, it is necessary to solve the following problems:

- analysis of operational loads acting on the material of the cannon barrel during firing,
- development of structural schemes of new strengthening technological equipment, suitable for effective strengthening treatment of the barrel channel of large-calibre cannons.

MATERIAL AND METHODS

Strengthening by surface plastic deformation of the inner surface of artillery cannon barrels through the proposed technology of vibration-centrifugal strengthening treatment is carried out as follows. A strengthening device (Fig. 1) includes an electric drive (1) and a cylindrical hardener (2). The hardener has deforming bodies (3) that are rotatably placed on its outer surface and take the form of hardened steel balls or carbide deforming bodies of a special configuration. The device is located inside the cannon barrel (4) being processed. The electric drive (1) and the cylindrical hardener (2) are connected to each other by a mechanism (5) that transmits torque and rotational motion. A feature of the rotational motion transmission mechanism (5) in this device is that, in addition to transmitting torque to the hardener (2) with deforming bodies (3), it also facilitates the rotational movement of the hardener around the symmetry axis of the cannon barrel (4). For this purpose, the mechanism (5) employs either a cardan or flexible shaft.

When a voltage is applied to the drive electric motor (1), the torque from its shaft is transmitted through the rotating motion transmission mechanism (5) – either a cardan or flexible shaft – to the hardener, which thus acquires a rotating motion with a frequency corresponding to the rotational speed of the electric drive shaft (1).

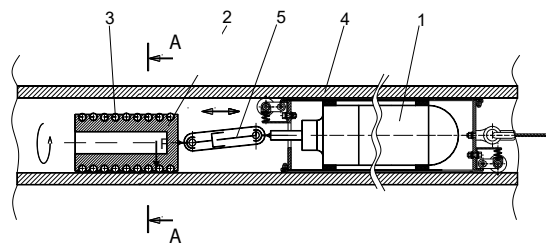


Fig. 1. Device for strengthening the cannon barrel (description in the text)

Source: own work.

In Figure 1, the directions of movement and rotation of the hardener (2) are indicated by arrows. Since the hardener (2) with deforming bodies (3) is designed with an eccentric displacement of its mass centre and axis of rotation relative to the geometric axis of the treated surface, the hardener, under the influence of the torque applied to it, self-engages in the mode of planetary rolling motion along the internal treated surface via its outer cylindrical surface.

To ensure this working rolling movement functions correctly and that the quality of the strengthening treatment is adequate, the geometric dimensions and parameters of the strengthening movement are selected to fulfil a relationship (Fig. 2):

$$\varepsilon = \frac{\sigma_m \cdot d^2 \cdot l}{50 \cdot m \cdot D \cdot n^2}, \quad (1)$$

where:

- ε – eccentricity of the mass centre of the hardener (2) relative to the geometric axis of the machined surface of the barrel (4) of the cannon,
- σ_m – yield point of the material of the strengthened cannon barrel (4),
- d – the diameter of the processed surface resulting from the impact contact of the deforming body with the cannon barrel (4),
- l – length of the external cylindrical surface of the hardener, on which the deforming bodies are installed.
- m – mass of the hardener (2) with deforming bodies (3),
- D – diameter of spherical deforming bodies,
- n – rolling frequency of the hardener (2) on the inner surface of the cannon barrel (4),
- l – length of the external cylindrical surface of the hardener, on which the deforming bodies are installed.

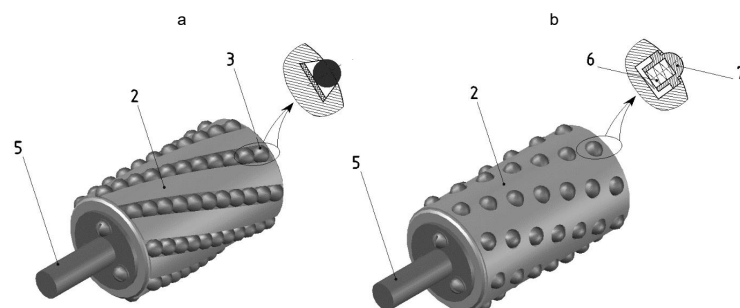


Fig. 2. Reinforcement of the inner surface of the cannon barrel with deforming bodies in the form of hardened steel balls (a) and hard alloy deforming bodies (b), (description in the text)

Source: developed by the authors.

During the rolling movement of the hardener along the internal processing surface of the cannon barrel (4), the hardener is subjected to the action of a centrifugal force F , the rotating vector of which is set in the centre of the hardener's mass and runs perpendicularly to the geometric axes of the hardener and the treated surface (Fig. 1). In Figure 1, the direction of action of the centrifugal force is shown by an arrow with the letter F .

The magnitude of this centrifugal force F is proportional to the mass m and eccentricity of the hardener ε and the square of the circular frequency n of its rolling motion. It is determined as follows:

$$F = m \cdot \varepsilon \cdot \omega^2, \quad (2)$$

where:

$\omega = 2\pi n$ – circular frequency of the rolling motion of the hardener.

At any time, the hardener contacts the treated surface of the barrel (4) through deforming bodies (3); for example, hardened steel balls placed along the cylindrical outer surface of the hardener. The contact with the duty group of deforming bodies located along the forming hardener occurs with impact interaction.

The rolling movement of the hardener (2) along the internal machined surface of the cannon barrel (4) is carried out simultaneously with the uniform movement of the strengthening device along the generatrix of the surface being hardened and the axis of the barrel. This ensures a uniform strengthening of the treated surface both along the circumference of its cross-section and along the length of the generatrix. If it is necessary to increase the thickness of the strengthened layer of material on the treated surface, movements of the hardening device along the axis of the barrel (4) are repeated or the mass of the hardener (2) can be increased.

After the completion of the first stage of the strengthening treatment of the inner surface of the cannon barrel (4), the cylindrical hardener (2) with spherical deforming bodies (3) of hardened steel is disconnected from the electric drive motor (2) and a similar hardener with spring-loaded hard alloy elastic elements (6) is attached. The second stage of strengthening treatment using carbide deforming bodies (7) is carried out similarly to the first one.

In this stage, at the points of impact contact of the carbide deforming bodies (7) with the already hardened inner surface of the cannon barrel (4), due to the transfer of microparticles of the powdered carbide alloy from which these deforming bodies are made of, the transfer of blocks of carbide molecules into the roughness cavities occurs at the molecular level. Then, since the cylindrical hardener (2) is rolled along the inner surface of the barrel (4) with a frequency equal to the rotational speed of the shaft of the electric motor of the drive (1), preferably equal to 16 Hz or 24 Hz, each of several hundred carbide deforming bodies (2) arranged on the hardener (2) causes 16 blows on the processed trunk surface per second. Since each blow of the deforming body (7) is accompanied by the transfer of hard alloy microparticles to the treated surface, the processed inner surface of the cannon barrel (4) is covered with a uniform layer of hard alloy pressed into the unevenness of the surface layer of the barrel metal. Moreover, each subsequent blow to a hard alloy microparticle already applied to the metal barrel not only adds the next portion of material but also “presses” the previous hard alloy microparticles into surface irregularities. Thanks to the gluing of carbide microparticles into the roughness of the barrel surface, such a carbide coating does not peel off from the thickness of the base material, connecting to it at the level of micro-welding. Since, during processing the hardener (2) with hard alloy deforming bodies (7) moves along the geometric axis of the hardened barrel (4), the entire inner surface of the barrel is covered with a uniform thin layer of hard alloy coating, having a thickness of several tens of microns. Despite the insignificant thickness of such a hard alloy coating on the inner surface of the cannon barrel, due to the high melting point, this coating will reliably resist the burnout of microparticles of the barrel metal when the cannon is fired.

In the technological process of manufacturing a cannon barrel, this two-stage strengthening treatment is the final finishing operation.

RESULTS AND DISCUSSION

The second stage of strengthening treatment, in accordance with this utility model, was carried out using hard alloy deforming bodies made of VK6 alloy, formed by sintering. The configuration of hard alloy deforming bodies and their location on reinforcement (2) is shown in Figure 2b. The diameter (D) of their spherical impact part was 10 mm. Strengthening treatment with carbide deforming bodies, in order to apply a carbide coating to the inner surface of a cylindrical sample reinforced with hardened steel balls, was carried out in three alternating passes along the generatrix of this cylindrical sample equal to 100 cm.

Measurements of the thickness of the hardened layer on the inner surface of the cylindrical sample after strengthening with hardened steel balls were carried out on ring samples cut from the hardened part using a metal microhardness measuring device PMT-3. Depending on the main technological parameters of the strengthening treatment with hardened steel balls, namely the mass of the hardener, the frequency of its rolling movement along the inner surface of the barrel, the speed of movement of the hardener along the generatrix of the fastening surface and the number of repeated transitions, the strengthening depth varied in the range of 0.1–0.2 mm.

The thickness of the VK6 hard alloy coating applied with hard alloy deforming bodies was measured on thin sections of samples treated by hardening using a Nikon E200 microscope with 100 $\times$ magnification. Depending on the aforementioned technological parameters, it varied in a range from several tens to hundreds of microns.

A comparative test of the effectiveness of the proposed method of step-by-step hardening of the inner surface of cylindrical parts was carried out based on data from wearing tests on hardened samples, conducted on an experimental installation designed to determine the wear resistance of materials. This installation followed the scheme of a standardised Pin-on-Disk Test type (ASTM G99) installation for testing material wear. Its standardised technique involves measuring wear between two surfaces, one being the surface of the test piece and the other being the surface of a rotating disk. The wear of three groups of samples was compared, namely the original non-strengthened samples made of alloyed structural steel grade 12XH3A, whose characteristics are close to those of the material used in cannon barrels, and similar samples subjected to hardening treatment by deforming bodies. Testing of samples from all the aforementioned groups was preceded by exposing them to a flame of alcohol vapours for 5 min to simulate the effect of flame and powder gases accompanying cannon shots on the metal of cannon barrels.

Experimental studies revealed that the wear resistance of the samples with the surfaces strengthened by hardened steel deforming bodies and subjected to high-temperature treatment is 35–40% higher than that of non-strengthened similar samples. It was established that the wear resistance of the samples strengthened in stages with steel and hard alloy deforming bodies is 25–30% higher than that of samples strengthened only with steel deforming bodies. In general, a comparison of the wear resistance of non-strengthened samples and those strengthened in stages with hardened steel and hard alloy deforming bodies indicates that two-stage strengthening treatment can increase the wear resistance of steel parts by 60–70%. Of course, taking into account the entire complex of negative factors affecting the metal of cannon barrels, such as the combination of high temperatures with enormous pressures accompanying a cannon shot, the effect of strengthening treatment will be significantly reduced. However, thanks to the two-stage strengthening with the final formation of a hard alloy coating on the inner working surface of the cannon barrel, it is reasonable to hope for an increase in the durability of cannon barrels by 20–25%. The true magnitude of changes in the durability of large-calibre cannon barrels reinforced alternately with hardened steel and carbide deforming bodies can only be established on the basis of data from so-called full-scale bench or field firing tests.

The advantage of the method for increasing the durability of artillery barrels, in accordance with the proposed utility model, is that the carbide coating applied to the inner surface of the cannon barrel can significantly

enhance the heat resistance of the material under high-temperature operating conditions. The presence of the carbide coating provided by the proposed method manifests itself positively in the following aspects:

- it forms a so-called thermal barrier – an obstacle that reduces heat transfer to the main body of the barrel metal, which helps reduce overheating of the barrel metal and results in decrease in strength,
- it increases the resistance of the metal against oxidation and corrosion – the formed carbide protective layer of the metal is resistant to chemical attack and reduces the rate of oxidation of the material and, accordingly, its corrosion,
- it protects the structure of the surface layer of the metal, improving its resistance to deformation and cracking under the influence of high temperatures.

CONCLUSIONS

1. A fundamentally new method of vibration-centrifugal strengthening treatment has been created, belonging to the group of methods of surface plastic deformation. It is characterised by providing a significant level of deformation energy for the material of the parts being strengthened. The method falls within the category of dynamic surface hardening techniques, delivering a hardening layer thickness of 0.15–0.20 mm on the internal surfaces of cylindrical long parts. Due to the substantial energy of the impact interaction between the tool and the material of the workpiece, residual compressive stresses with a significant gradient are formed in its surface layers. As a result, this enhances the strength and reliability of the hardened parts.
2. It has been proposed that new designs of hardeners be used for a two-stage strengthening treatment employing the method of vibration-centrifugal strengthening for the barrel channels of large-calibre artillery cannons. The proposed hardeners are simple in design, energy-saving, and do not require highly qualified maintenance personnel for upkeep.
3. During the final, second stage, strengthening the inner surface of cannon barrels with carbide deforming bodies made of VK6 alloy ensures an increase in the heat resistance of the barrel material and its resistance to high-temperature heating during firing.

Authors' contributions

Conceptualisation: I.A., I.S., O.S.; methodology: I.A., I.S., O.S.; validation: Y.R., O.B.; formal analysis: Y.R., O.B.; investigation: D.B., N.K.; resources: D.B., N.K.; writing – original draft preparation: I.A., I.S., O.S.; writing – review and editing: D.B., N.K., M.C.; visualisation: I.A., I.S., O.S.; supervision: I.A.; project administration: N.K.; funding acquisition: N.K.

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

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ZWIĘKSZANIE WYTRZYMAŁOŚCI LUF DUŻEGO KALIBRU POPRAZEC POWIERZCHNIOWE WZMOCNIENIE ODKSZTAŁCENIA PLASTYCZNEGO

STRESZCZENIE

W artykule przedstawiono technologię wzmacniania powierzchni wewnętrznej luf armat i czołgów poprzez powierzchniowe odkształcenia plastyczne. Zaleca się przeprowadzenie obróbki wzmacniającej w dwóch etapach – kulkowanie naporowe wewnętrznej powierzchni roboczej lufy kulkami ze stali hartowanej, a następnie nałożenie żaroodpornej powłoki z twardego stopu z odkształcalnymi korpusami ze stopu VK6. Ustalono, że w wyniku tej obróbki wzmacniającej w przypowierzchniowej warstwie materiału otworu wiertniczego powstają szczątkowe naprężenia ściskające, zwiększają się jego mikrotwardość powierzchniowa oraz odporność metalu powierzchni roboczej lufy na wypalenie i pękanie. Łącznie zwiększa to odporność materiału lufy na zużycie podczas strzałów. Powstał projekt urządzenia wzmacniającego do tego zabiegu. Składa się ono z cylindrycznego utwardzacza z odkształcalnymi korpusami, elektrycznego silnika napędowego oraz mechanizmu przenoszenia momentu obrotowego z wału silnika na utwardzacz. W procesie obróbki wzmacniającej urządzenie przesuwa się wzdłuż kanału lufy, utwardzacz toczy się po obrobionej powierzchni wewnętrznej lufy i kulkuje jej materiał. Przewidywana grubość wzmocnienia wynosi 0,15–0,20 mm, grubość nałożonej powłoki z twardego stopu dochodzi do 100 µm.

Słowa kluczowe: działą, twardy stop, powłoka, zużycie, wzmocnienie powierzchniowe, kulkowanie naporowe

THE IMPACT OF BIM AND GIS ON THE EFFICIENCY OF IMPLEMENTING CONSTRUCTION PROJECTS

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ABSTRACT

The integration of building information modelling (BIM) and geographic information systems (GIS) plays a key role in modern civil engineering, improving the efficiency of construction project execution. This article focuses on specific aspects of this integration, such as spatial and engineering data management, spatial analysis, and optimisation of construction processes. Using the example of the Central Communication Port (*Centralny Port Komunikacyjny* – CPK) in Poland, it illustrates how BIM enables detailed digital representations of the physical characteristics of construction projects, supporting planning and management, while GIS provides tools for advanced spatial and environmental analyses. The integration of both technologies allows for precise representation of the spatial context, enhances resource management, reduces construction costs and risks, and supports interdisciplinary collaboration at various stages of the project. The article also discusses challenges, such as the lack of standardised data exchange procedures and the need for specialised training essential to acquire knowledge enabling full use of the potential of BIM and GIS. The aim of the work is to analyse the impact of BIM and GIS integration on construction project management, with particular emphasis on data management processes and spatial analyses.

Keywords: BIM, GIS, Central Communication Port, AI

INTRODUCTION

Contemporary civil engineering increasingly relies on advanced technologies and methodologies aimed at improving project execution efficiency. Two of the most important ones playing a crucial role in this process are building information modelling (BIM) and geographic information systems (GIS). BIM is a methodology for managing information about construction projects or structures throughout their entire lifecycle – from conception, through design and construction, to operation and demolition. BIM enables the creation and utilisation of digital representations of physical and functional characteristics, allowing for better planning, designing, building, and managing of constructions (Zawada, Rybak-Niedziółka, Donderewicz & Starzyk, 2024). Nonetheless, GIS technologies are used for collecting, analysing, and presenting geographic data. GIS allows for the integration of spatial data with other data types, enabling the creation of comprehensive models and maps that support decision-making processes in construction. GIS is used, among other things, for spatial analysis, urban planning, infrastructure management, and risk assessment (Sunny, 2024).

The combination of BIM and GIS in construction projects brings numerous benefits. The integration of these methodological and technological solutions allows for the creation of more precise and comprehensive models that take into account various aspects such as architecture, linear and energy infrastructure, spatial context, and more. This enables better resource management, cost and time reduction, and minimisation of construction-related risk factors. One example of BIM and GIS integration is the ability to accurately plan construction material delivery routes, perform environmental impact analyses, and assess the accessibility of construction sites. Moreover, the use of BIM and GIS can increase the transparency of construction processes and facilitate communication among all project participants – from designers and contractors to developers. This, in turn, allows for more effective monitoring of project progress, quicker responses to emerging issues, and the implementation of necessary adjustments.

The article presents an analysis and case study illustrating how the integration of BIM and GIS impacts the efficiency of construction project execution (Fig. 1). It will analyse both the benefits of their use and the challenges that must be overcome to fully realise their potential (Wang, Pan & Luo, 2019; Borkowski & To Duc, 2024).

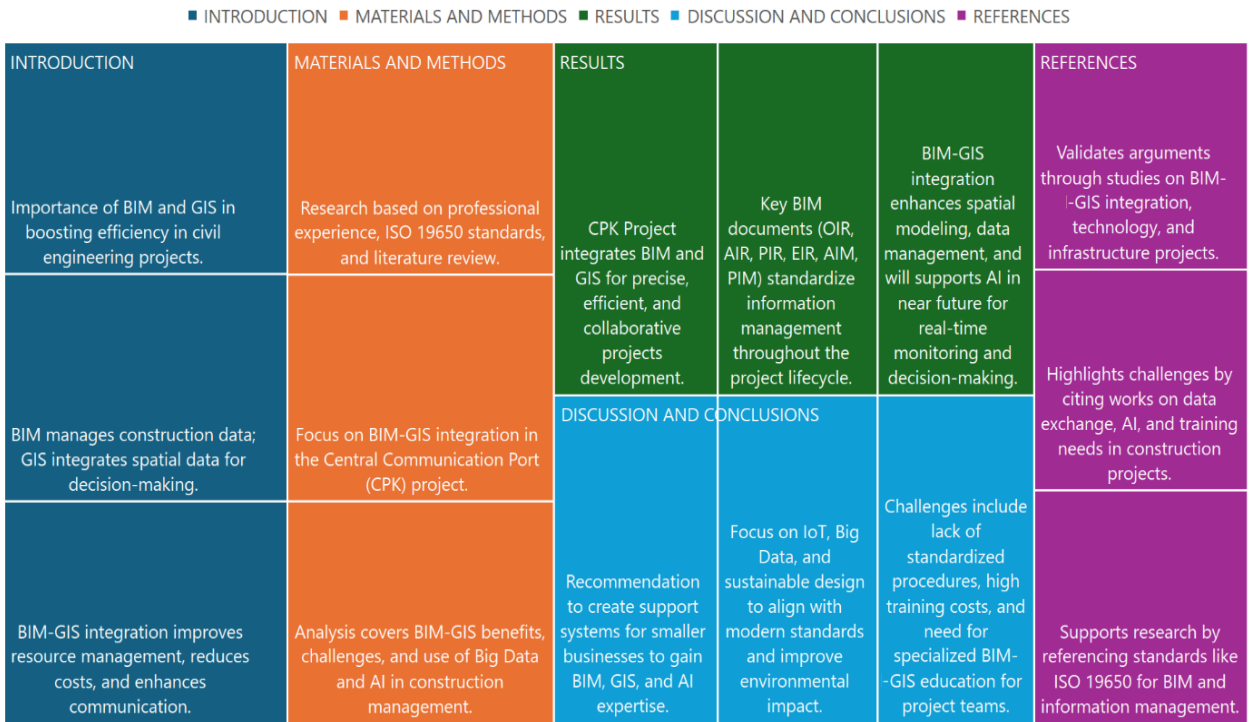


Fig. 1. Article flowchart

Source: own work.

MATERIAL AND METHODS

In the preparation of this article, the authors drew upon their professional experience and practical knowledge. Additionally, the research approach employed to examine the integration of BIM and GIS in construction projects, with a particular focus on the Central Communication Port (CPK) in Poland, is discussed.

The research methodology is based on three main elements (Fig. 2): (1) professional experience; (2) ISO 19650 standards; (3) literature review and critique. It is important to emphasise the significance of the research team’s expertise in BIM and GIS, which provided an opportunity for practical evaluation and insights regarding the application of these technologies in real projects. Subsequently, an analysis of the ISO 19650 standards (British Standards Institution [BSI], 2018a, 2018b, 2020a, 2020b, 2022), which pertain to information exchange in construction processes in the context of BIM, was conducted to formulate observations related to the integration of BIM and GIS (BS EN ISO 19650-1:2018; BS EN ISO 19650-2:2018; BS EN ISO 19650-3:2020; BS EN ISO 19650-5:2020; BS EN ISO 19650-4:2022). This qualitative data helps to understand the operational landscape and the effectiveness of these technologies in managing projects in the digital world. Finally, a comprehensive literature review was conducted, which allowed for identifying trends within the context of existing research. This review highlighted the benefits and challenges associated with the integration of BIM and GIS. Database search engines used included ResearchGate, Web of Science, Google Scholar, Scopus, the Acta Scientiarum Polonorum archive, and the Knowledge Base of the Warsaw University of Life Sciences (SGGW). An attempt was made to extract publication topics using the following criteria: research conducted exclusively in Polish or English, carried out between 2018 and 2024, utilising keywords related to the subject of this study. Subsequently, the material was gradually narrowed down to refine the scope. It is believed that this methodology enabled the identification of the most important issues related to the topic, while also addressing aspects of big data, data science, and artificial intelligence (AI) in the construction project management process.

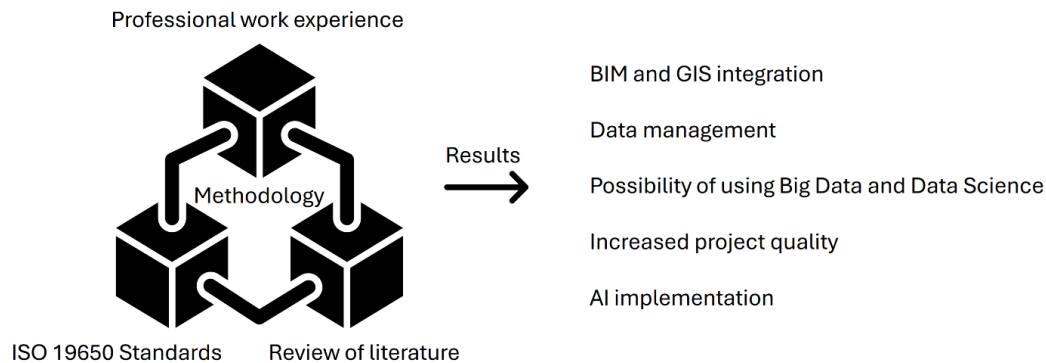


Fig. 2. Research methodology diagram

Source: own work.

RESULTS

Integration of BIM and GIS: A case study of the Central Communication Port

The Central Communication Port (CPK) is one of the most significant infrastructure projects in Poland in recent years. This project includes the construction of a new international airport as well as the development of a railway and road network (Uchwała Nr 201 Rady Ministrów z dnia 24 października 2023 r.). To execute this massive undertaking, CPK is adopting modern approaches and technologies such as BIM and GIS (Centralny Port Komunikacyjny, n.d.). The integration of BIM and GIS plays a crucial role in ensuring efficiency, precision, and collaboration among various project teams. Further, we discuss the aspects of integrating

these two technologies, based on CPK's internal documents concerning information requirements. Within the BIM methodology, several key documents play an essential role in managing information across different stages of the project – from planning, through all phases of the design process, to demolition. These documents assist in standardising processes, managing data, and facilitating collaboration among different teams. All guidelines and project files are located in a single, central data repository, which is the Common Data Environment (CDE) Bentley ProjectWise platform (Fig. 3).

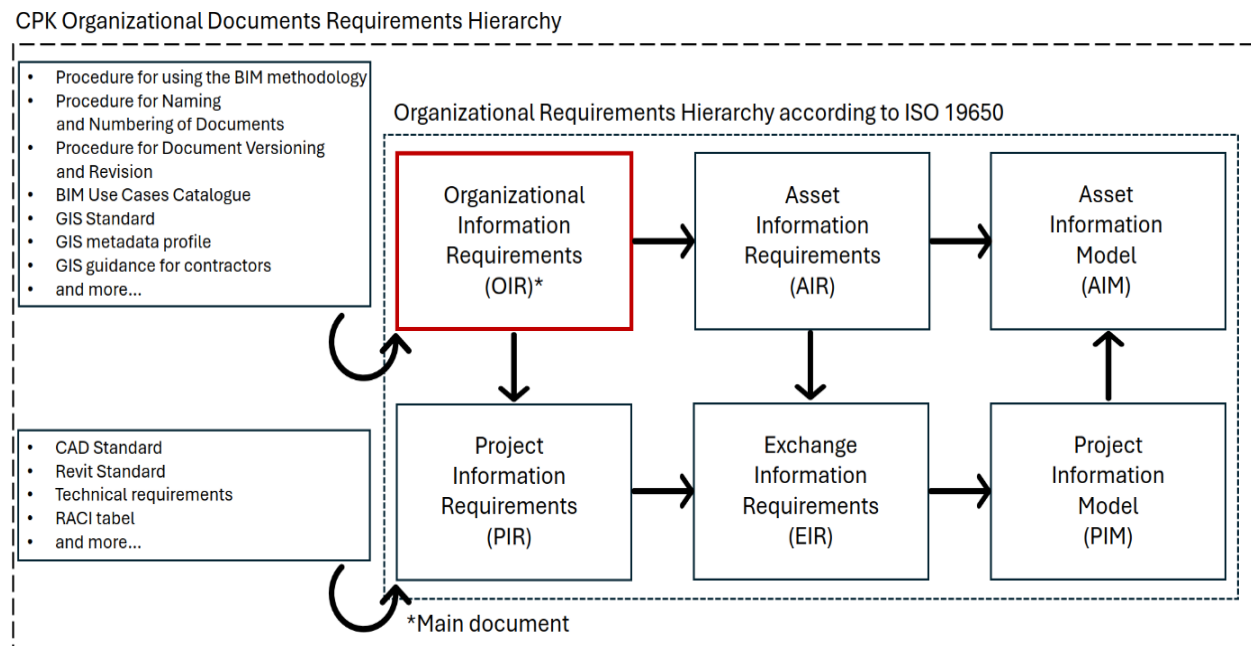


Fig. 3. Central Communication Port (CPK) organisational documents requirements hierarchy

Source: own work based on ISO 19650 and BIM and GIS Central Communication Port (CPK) procedures.

The organisational information requirements (OIR) is a document that specifies the information needs of an organisation at a strategic level. The OIR define the necessary information for effective management, monitoring, and achievement of organisational goals throughout the project lifecycle. It is a crucial document that ensures all organisational actions align with its long-term strategy and objectives. Another document is the asset information requirements (AIR), which outlines the information needs related to managed organisational assets, such as buildings, infrastructure, or equipment. The AIR is essential to ensure that all asset information is accurate, up-to-date, and available when needed. The asset information model (AIM) is an integrated model that contains all data and information related to asset management. The AIM collects and processes information throughout the asset lifecycle, from planning and construction to operation and eventual decommissioning. With the AIM, organisations can effectively manage their assets and make informed decisions. The project information requirements (PIR) is a document that specifies specific information needs for individual projects. The PIR considers technical, operational, and managerial requirements, ensuring that all necessary project information is collected and processed to enable effective project management. Based on the PIR, the employer's information requirements (EIR) are prepared. The EIR is document created by the employer, defining information expectations and requirements for contractors and suppliers. The EIR ensures that all project participants have clear and understandable

guidelines regarding the employer's information expectations, helping to avoid misunderstandings and ensuring that the project is executed according to its requirements. The project information model (PIM) is a detailed model containing all information collected and processed during the execution of a construction project. The PIM is a key tool in project management, allowing efficient gathering, analysis, and sharing of information at all project stages, from planning through execution to completion. Thanks to the PIM, all stakeholders have access to current and accurate information, facilitating collaboration and coordination (Godager, Mohn, Merschbrock, Klakegg & Huang, 2022).

BIM documentation in the Central Communication Port

The scope and purpose of key documents according to ISO 19650 are presented in Table 1. These documents standardise information exchange between individual projects at all stages of the entire project process, such as for the CPK. It's important to note that all these documents are interconnected, and their provisions complement each other rather than exclude one another (Anger, Łaguna & Zamara, 2021; Kasznia, Magiera & Wierzowiecki, 2022).

Table 1. Contents and targets for basic BIM documents

Document	Content	Target
OIR	Key objectives of the organisation and their impact on information needs.	Ensuring that the information needed for decision-making at the strategic level is available, accurate, and up to date.
	Requirements for data collection and processing.	
	Information management standards and procedures.	Facilitating effective information management at all stages of the project.
	Tools and technologies supporting information management.	
AIR	Specifications of information about resources needed to manage them throughout their lifecycle.	Ensuring that information about resources is complete, accurate, and accessible throughout their entire period of use.
	Requirements for data related to maintenance, operations, and resource utilisation.	Supporting effective resource management and decision-making regarding their exploitation.
	Standards and procedures for collecting and processing information about resources.	
AIM	Geometric data, attributes, and technical properties of resources.	Enabling central storage and management of resource information.
	Information on maintenance, operations, and resource utilisation.	Supporting decisions regarding maintenance, modernisation, and resource management.
	History of changes and updates to resources.	
PIR	Detailed requirements for the data needed to implement the project.	Ensuring that all project teams have access to the necessary information that complies with organisational and project standards.
	Guidelines for 3D modelling, interbranch coordination, and data management.	Facilitating effective collaboration and coordination of activities within the project.
	Requirements for reporting and data reviews.	
EIR	The client's expectations regarding the scope, format, and quality of information provided by the contractors.	Ensuring that contractors provide information in accordance with the requirements of the contracting authority.
	Requirements for BIM standards, procedures, and tools.	Facilitating the client's monitoring and management of the project.
	Guidelines for reviewing and approving provided information.	

Source: own work based on ISO 19650.

In the CPK, in addition to the above-mentioned documentation, we also distinguish:

(A) – The document revision and versioning procedure. It is crucial for maintaining the accuracy and relevance of information in the CPK project. According to this procedure, every change in documentation must be meticulously tracked, versioned, and approved. This process ensures that all teams have access to the latest and verified information, minimising the risk of errors and misunderstandings.

(B) – The document naming and numbering procedure, which signifies standardised naming and numbering of documents, is essential for maintaining order and transparency in a large project like the CPK. This procedure defines clear rules for naming and numbering, facilitating identification, search, and documentation management. As a result, all teams can quickly and easily find the necessary information.

(C) – The GIS standard, a document aimed at describing the requirements of the GIS ordering party, in which the principles of creating GIS data, basic data formats (vector, raster, databases, attribute data, layer styles, map compositions), technical requirements, and rules for GIS data naming are specified. The standard is closely related to the OIR document, ensuring effective integration with BIM.

(D) – Other BIM documents and standards refer to documentation created dynamically with the increase in the number of projects in the airport and railway subprograms of the CPK. This is due to the stages and specificity of projects that cover all industries. The entire documentation is created by the central BIM team and reviewed by industry experts the company employs.

Each of the mentioned components plays a crucial role within BIM and GIS, providing the structure, standards, and procedures necessary for effective information management in construction projects. They ensure consistency, quality, and accessibility of data, which translates into the efficiency of project execution and management at every stage of the project lifecycle (Centralny Port Komunikacyjny, n.d.).

The possibilities offered by the integration of BIM and GIS in management methods

Integration of BIM and GIS in the CPK project brings numerous benefits, including improved planning, spatial analysis and data management (Sani & Abdul Rahman, 2018; Syed Mustorpha & Wan Mohd, 2019; Shi, 2024). The main aspects of this integration are detailed in the next subchapters.

Integrated spatial modelling

This concept integrates detailed BIM models with GIS data, allowing for a more precise and realistic representation of the built environment. This integration enables:

- Localisation and contextualisation of projects: BIM models can be embedded in real geographic locations, facilitating planning and analysis.
- Spatial analysis: Integration with GIS allows for advanced spatial analyses (such as the visual impact on the landscape, visibility analysis of the building from various key observation points, and hazard assessment) as well as environmental impact evaluation.
- Digital terrain models (DTM): These models enable detailed analysis and visualisation of the topography, supporting accurate spatial planning and natural resource management. They also facilitate the prediction of environmental hazards, such as floods or landslides, through terrain modelling and analysis of its properties.

Data management and collaboration

Integration of BIM and GIS supports better data management and collaboration between teams. Key elements include:

- Common data standards: These enable information exchange between different systems and tools, improving data efficiency and consistency.
- Data centralisation: All data is stored in a central repository, which facilitates accessibility and updates.

Using GIS in the operational phase

GIS also plays a crucial role in the operational phase of the CPK. Through integration with BIM, it enables:

- Monitoring and managing infrastructure: GIS allows for tracking the technical condition of buildings and infrastructure, which is essential for maintaining them in good condition using software such as ArcGIS or QGIS.
- Resource and operations management: GIS supports the management of resources such as energy, water, and waste, contributing to increased operational efficiency.

It is worth noting that preparations are underway for implementing AI to further enhance and expedite project management within the company. The task is being led by the co-author of this article, Karol Zawada, who serves as the BIM manager for projects in the airport subprogram. The plan involves integrating the CDE platform (Bentley ProjectWise), where all project documentation is stored, with Microsoft Power BI through a connector (Fig. 4). This integration will allow real-time monitoring of vast amounts of data, enabling trend observation, potential problem identification, carbon footprint management, and rapid decision-making.

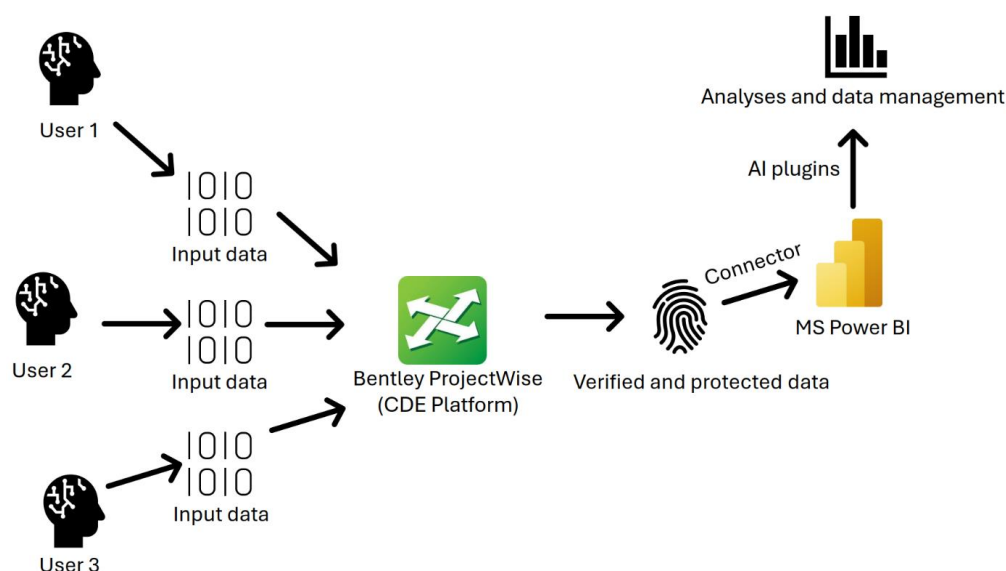


Fig. 4. Diagram of one of the future example strategies for implementing artificial intelligence in Central Communication Port (CPK) projects

Source: own work.

The implementation of AI in this context aims to automate data analysis and generate reports and forecasts, significantly increasing the efficiency of project teams. AI will, for example, predict delays, analyse costs and resources, and suggest optimal courses of action based on extensive data sets leveraging big data and data science. The system will also be able to recognise patterns in the data and propose adjustments to schedules and resource allocation, minimising the risk of errors and enhancing planning accuracy. With integration into Microsoft Power BI, data will be presented in the form of interactive dashboards, allowing managers quick access to key information. This solution has the potential to significantly improve transparency and communication within project teams, enabling better management at both strategic and operational levels (Chen et al., 2024; Starzyk et al., 2024).

The use of BIM methodology and integration with GIS in the CPK project brings numerous benefits, including improved planning, analysis, data management, and collaboration. Procedures related to information requirements, revision and versioning, as well as document naming and numbering provide a solid foundation for the effective implementation of these technologies. As a result, the CPK project has the potential to become a model for other large-scale infrastructure projects worldwide (Kurek, 2023).

DISCUSSION AND CONCLUSIONS

An important recommendation would be to establish a regulatory system and support mechanisms for smaller businesses, allowing them to develop the necessary expertise at every stage of managing and executing engineering projects, not just those on the scale of CPK. It is believed that the integration of BIM methodology, GIS, and AI, with particular attention to the Internet of Things (IoT) and big data, will provide opportunities for more organised and effective professional training programs tailored to new problems and challenges in the future. This will create an opportunity to align with contemporary standards, design norms, and legal requirements while also focusing on ecological and sustainable design and considering the positive impact on the environment. These aspects are characterised as positive outcomes resulting from the implementation of improvements in integrating new technologies. Despite the benefits, the study highlights several challenges that need to be addressed. These include the lack of standardised procedures for data exchange between BIM and GIS and the need for specialised training for team members. These barriers may hinder the full utilisation of both technologies in construction projects, and further research aimed at minimising these obstacles will be valuable across multiple dimensions and can undoubtedly be considered essential (Sun & Kim, 2022; Saleh, Elhendawi, Darwish & Farrell, 2024).

The establishment of a multi-layered BIM framework in the CPK project exemplifies the implementation of contemporary construction standards. Considering the ongoing revolution driven by AI development, the proposed system aims to address both the threats and opportunities presented by this technology. The article outlines the various stages of project creation and the procedures designed to ensure the most efficient communication while maintaining transparency in decision-making processes. The demonstrated action plan is based on a multi-level competency configuration that, on the one hand, ensures the feasibility of the project and, on the other, provides a clear sequence for decision-making. Despite the complexity of the procedure, its advantage lies in the clearly defined decision-making structure. Overall, the development of a BIM-based system for designing and managing the CPK project offers a chance to create a universal model for handling such large-scale projects. The procedures developed through extensive consultations can serve as a foundation for managerial activities in large projects at every planning and execution stage. The educational aspect is crucial here. Greater awareness of the usefulness of the BIM environment in engineering and business processes is needed, as it represents not only a tool but also an opportunity to create a comprehensive decision-making process. The detail of the developed operational model should not intimidate potential participants but rather reassure them of the system's preparedness for most eventualities that might arise during the management of a large project. Creating such multi-layered procedures for large projects requires imagination combined with the experience of the entire management team. Given that BIM spacial operations will be increasingly driven by the need for detailed and continuous decision-making in engineering projects, the creation of competent teams is essential, with CPK serving as a good example. Thus, a training system that includes not only senior management but also mid-level executive teams is necessary. Such training should encompass the entire decision-making group involved in the project, providing a chance to develop skilled personnel ready for the challenges of demanding and large-scale projects. Unfortunately, these needs also come with associated risks. Currently, the most pressing issue is the lack of knowledge due to insufficient education. Equally important are the high costs, which can pose a significant problem in the financial accounting of

large projects. The shortage of competent high and mid-level managers necessitates specialised training, which remains limited and expensive. The cost of acquiring these competencies can be a significant barrier to large project plans and implementations. Moreover, access to technology also incurs substantial financial demands. The software required for BIM management at various competency levels and for project creation still involves considerable financing. For large and very large projects with state or global developer teams, this can be a factor due to the high “return on competency”. However, challenges arise for small or medium-sized capital projects. If there is a continuity of contracts, investment in team training is feasible. Yet, for projects with less frequent repetition, such actions may be uneconomical, leading to fragmented solutions that rely on cheaper and older technologies.

The authors recommend implementing the statutory use of BIM methodology in public procurement. A nationwide BIM standard should be developed, closely based on the solutions and documentation established in the CPK, due to the scale and complexity of this project, which encompasses all possible industries. This will enable the effective and efficient use of BIM in projects. A prime example of unsuccessful BIM implementation in an infrastructure project commissioned by the General Directorate for National Roads and Motorways (*Generalna Dyrekcja Dróg Krajowych i Autostrad – GDDKiA*) is the Zator bypass. The project was delayed by several years due to discrepancies in the project documentation, poorly executed 3D models with many clashes, metadata deficiencies, and inconsistencies between the 2D and 3D documentation (Karolak et al., 2018; Poznańskie Inwestycje Miejskie, 2024). However, BIM methodology was successfully implemented in the Hinkley Point C Nuclear Power Plant project, in which the co-author of this article, Karol Zawada, participated for two years as a structural designer’s assistant, modelling reinforced concrete structures in the HL2-03 building that surrounded the nuclear reactor. The 2D documentation was generated from the 3D model only after all clashes were resolved, ensuring the transparency and accuracy of the project data (Zawada, 2023).

The limitations of the study include the lack of specific examples regarding the use and integration of BIM and GIS in large-scale projects. This article serves as an introduction to a series of publications concerning projects that are part of the CPK. The authors plan to write a paper on the program concept of roads (*konceptcja programowa dróg – KPD*) for the CPK, where the engineering challenges related to these technologies, the flow of all project documentation, the software used, the configuration of the CDE platform, and many other aspects will be described in detail.

Authors’ contributions

Conceptualisation: K.Z. and M.D. and A.G.; methodology: K.Z. and M.D.; validation: K.R.N. and A.G.; formal analysis: K.Z. and M.D. and K.R.N.; investigation: K.Z.; resources: K.Z. and A.G.; data curation: M.D.; writing – original draft preparation: K.Z. and M.D.; writing – review and editing: M.D. and K.R.N. and A.G.; visualisation: K.Z.; supervision: M.D. and K.R.N.; project administration: K.Z. and A.G.; funding acquisition: K.R.N.

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

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WPŁYW BIM ORAZ GIS NA EFEKTYWNOŚĆ REALIZACJI PRZEDSIĘWZIĘĆ BUDOWLANYCH

STRESZCZENIE

Integracja modelowania informacji o budynku (BIM) oraz systemów informacji geograficznej (GIS) odgrywają kluczową rolę we współczesnej inżynierii lądowej, gdyż poprawiają efektywność realizacji projektów budowlanych. W artykule skupiono się na konkretnych aspektach tej integracji, takich jak: zarządzanie danymi przestrzennymi i inżynieryjnymi, analiza przestrzenna oraz optymalizacja procesów budowlanych. Na przykładzie Centralnego Portu Komunikacyjnego (CPK) w Polsce przedstawiono, jak BIM umożliwia szczegółowe cyfrowe odwzorowanie cech fizycznych obiektów budowlanych, co jest wykorzystywane w planowaniu i zarządzaniu przedsięwzięciami budowlanymi, a GIS zapewnia narzędzia do zaawansowanych analiz przestrzennych i środowiskowych. Integracja obu technologii pozwala na precyzyjną reprezentację kontekstu przestrzennego, usprawnia zarządzanie zasobami, redukuje koszty i ryzyko budowlane oraz wspiera współpracę międzybranżową na różnych etapach projektu. W artykule omówiono również wyzwania związane z wykorzystaniem BIS i GIS, m.in. brak ustandaryzowanych procedur BIM oraz konieczność szkoleń specjalistycznych niezbędnych do zdobycia wiedzy umożliwiającej pełne wykorzystanie potencjału obu technologii. Celem pracy jest analiza wpływu integracji BIM i GIS na zarządzanie przedsięwzięciami budowlanymi z uwzględnieniem procesów zarządzania danymi i analiz przestrzennych.

Słowa kluczowe: BIM, GIS, Centralny Port Komunikacyjny, AI

QUANTITATIVE ASSESSMENT OF HYDROLOGICAL EFFICIENCY OF RAIN GARDEN DESIGN IN THE CONTEXT OF MANAGING THE VOLUME AND QUALITY OF STORM EFFLUENT

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ABSTRACT

Rain gardens are a popular element of green infrastructure, often integrated into the sponge city concept to address stormwater management issues. Such structures perform three main functions: reducing the volume of water runoff from the catchment area, reducing peak flows in the drainage system, which is critical for preventing overloading of the sewer network, and improving water quality, which contributes to the preservation of groundwater. The design of rain gardens is based on specific requirements and characteristics that determine their construction and calculation methods to achieve optimal parameters, such as area and depth. Scientometric analysis shows that significant research contributions are made by different countries, but most existing rain garden systems are based on general recommendations, which can lead to problems in their operation. The purpose of the work is to develop a model for calculating the main parameters of rain gardens and methods for assessing their hydrological efficiency in order to improve their implementation in the urban environment. A numerical model for calculating the effective area of a rain garden is presented, which considers one rain event and excludes overflow. Methods are proposed for evaluating three key functions of rain gardens in the context of stormwater management: a method for determining runoff reduction, a method for estimating annual runoff reduction, a method for peak runoff reduction, and a method for estimating total pollutant reduction.

Keywords: rain garden, storm drains, stormwater management, modelling, rain garden parameters

INTRODUCTION

With the continuous development of global urbanisation, its impact on the climate is becoming more and more obvious. In particular, such phenomena as the urban heat island effect, extreme heat and waterlogging of cities are observed. At the same time, global climate changes affect the spatio-temporal distribution of precipitation. The higher intensity of stormwater runoff, which is currently observed in many countries, in particular in Eastern Europe (Poland, Ukraine), is a consequence of the urbanisation of catchment areas, which is accompanied by an increase in the share of impermeable surfaces. Precipitation often takes the form of torrential rains: up to 3/4 of the average monthly rainfall can fall in 30 min, indicating that rains are becoming less frequent but more intense.

The interaction of impermeable areas with extreme and intense precipitation leads to the formation of local floods and to an increase in the speed of storm runoff of surface water (Guerreiro, Glenis, Dawson & Kilsby, 2017; Trach, 2020). To partially solve this problem, traditional drainage systems are used to divert rainwater from compacted surfaces to a centralised sewage system, treatment facilities, or the nearest water bodies.

However, the service life of such infrastructure systems has generally exceeded the planned period, and major repairs require high costs of materials and ongoing maintenance, so during heavy rainfall, these structures are usually unable to cope with large peak flows, which often leads to their overflow and flooding.

Urban areas that only have sewage systems that collect surface runoff and wastewater for discharge to sewage treatment facilities are in an even more difficult situation. Any sudden increase in surface runoff during torrential rain causes local floods and paralyses the entire system (Zhang et al., 2020b). Unfortunately, it is impossible to correct the situation in the short term, because improving the efficiency of the surface runoff system is, at best, very difficult and expensive. This is mostly due to the high density of urban buildings and the fact that sewage systems are laid deep underground.

As global warming continues, extreme weather events combined with urbanisation pose increased risks to humans and ecosystems (Giese, Rockler, Shirmohammadi & Pavao-Zuckerman, 2019). In particular, the projected changes in the duration of dry periods between precipitations have a negative impact on the quality of stormwater. Prolonged dry periods contribute to the accumulation of particulate matter and toxic pollutants on impervious urban surfaces, and heavy rainfall washes significant amounts of pollutants into water bodies through storm runoff. This increases the risk of contamination of receiving water bodies and makes it difficult to reuse stormwater without preliminary treatment (Kravchenko, Trach, Trach, Tkachenko & Mileikovskiy, 2024a).

Today, the term ‘sponge city’ is appearing more and more often in scientific literature, which indicates a growing interest in this concept. It involves the integration of natural and artificial elements to improve retention, infiltration and treatment of stormwater in the urban environment. More and more countries around the world are actively implementing the principles of the sponge city, aimed at effective management of runoff, reducing the risk of flooding, improving water quality and ensuring the resilience of urban infrastructure to climate change.

A sponge city is a concept that involves using the principles of a sponge to absorb rainwater and treat it further before returning it to the city’s drainage system. This is ensured by infiltration and purification of groundwater, which makes it possible to reduce surface runoff and prevent flooding (Fig. 1).

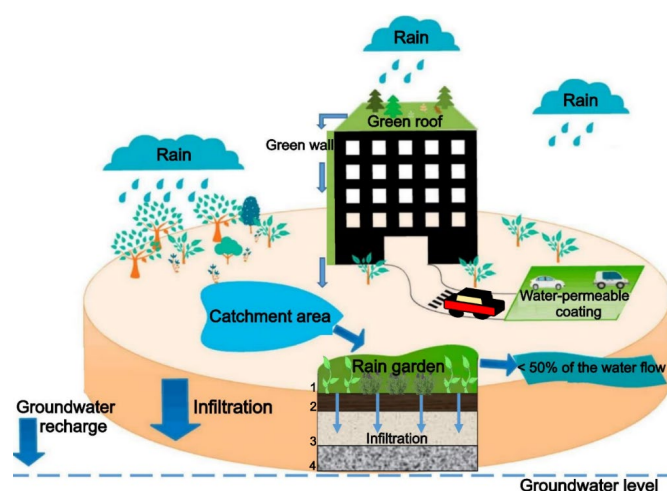


Fig. 1. Principles of stormwater management based on the sponge city concept

Source: adapted from Qi et al. (2020).

The rain garden should be designed with following main elements: 1 – plant layer; 2 – a layer of soil mixture for planting plants, 3 – infiltration/intermediate layer; 5 – a layer of gravel.

The concept of the sponge city is aimed at restoring the urban hydrological system by integrating environmentally friendly solutions, in particular, combining different types of green infrastructure (GI) and elements of urban infrastructure to form complex infrastructure systems. This makes it possible to efficiently collect, manage and reuse urban water, contributing to the sustainable development of urban areas and improving their adaptation to climate change.

As Zaręba et al. (2022) note: ‘sponge cities are used to mitigate the five main problems in the field of stormwater management in urban areas: water scarcity, waterlogging, water pollution, ecological degradation and the so-called city syndrome’.

Green infrastructure refers to methods aimed at restoring the hydrological cycle by incorporating natural components into the urban landscape that can increase rainfall interception and infiltration (Berland et al., 2017). This is a relatively new approach that has gained popularity as an effective means of reducing the destructive effects of floods and achieving a better balance between the needs of urbanisation and the needs of nature (Coleman, Hurley, Rizzo, Koliba & Zia, 2018).

In recent years, the number of studies related to the practice of GI in rainwater management has been progressively increasing. As a recent example, Ying, Zhang, Zhang and Bilan (2022) conducted a comprehensive review of the literature related to GI, examining publications published from 1995 to 2019. The analysis of the works, which were searched by the authors based on keywords, indicates that the majority of articles are focused on the study of GI in the field of stormwater management. Gao, Wang and Yang (2022) recently completed a scientific review of works related to GI published in 1999–2021, providing a lot of useful information on this topic. And within the framework of the study by Green et al. (2021), the role of GI in managing the risks of urban floods was studied. The authors analysed the specifics of using GIs to reduce urban flooding problems, exploring a number of challenges and priorities that need to be addressed in order to incorporate GIs into current stormwater management systems.

Green infrastructure includes any system that provides positive or sustainable environmental benefits, including such as permeable pavement, rainwater tanks, and solar panels, but the term ‘green’ directly refers to types of infrastructure where vegetation is an integral part of their design and functionality. Such systems include urban gardens, parks, forests, nature reserves, as well as systems that include engineering components, such as green walls, green coverings, rain garden structures, and wetlands (Sharma & Malaviya, 2021; Bruner, Palmer, Griffin & Naeem, 2023).

Rain gardens, often referred to as bioretention or bioinfiltration systems, have been recommended for local, near-source stormwater management due to their cost-effectiveness and positive effects on ecosystem restoration (Osheen & Singh, 2019).

These structures are usually located in lowland areas, and thanks to the infiltration and adsorption processes occurring in the system ‘plants – microbial population – structural layers’, effective cleaning of rainwater is achieved in a limited area. Rain gardens are mainly used to manage rainwater runoff from surfaces up to 1 ha. The main advantages of rain gardens include:

- reducing the volume of rainwater runoff from the area of the catchment basin (Shafique, 2016),
- reducing the speed of peak water flows in the sewage system, which is of particular importance for preventing hydrological overloading of the sewage network (Shuster, Darner, Schiffman & Herrmann, 2017),
- water quality control, which contributes to the preservation of groundwater (Morash et al., 2019).

For example, DeBusk and Wynn (2011) evaluated the effectiveness of a rain garden, into which stormwater flows from a parking lot, and showed a 99% decrease in peak water flow rates from the parking lot. A study conducted by Rezaei et al. (2019) using the stormwater management model (SWMM) of the US Environmental Protection Agency using rain gardens indicates that even small changes in rain garden

parameters such as water permeability, layer sizes and material selection, significantly affect the simulated peak flow.

The percentage reduction in the volume of stormwater diverted from the area of the catchment basin due to the use of rain gardens depends on the intensity of precipitation and its duration, as well as on the design features of the rain garden. The effectiveness of reducing the flow volume was investigated in various works (Brown & Hunt, 2011; Shafique & Kim, 2017; Zhang Ye & Shibata, 2020a).

According to Shafique and Kim (2017), the total percentage of runoff volume reduction is in the range from 50% to 98% for various studies. According to Zhang et al. (2020a), the reduction of runoff with the help of rain gardens ranges from 23% to 97%, depending on the climatic conditions in which the research was conducted. Therefore, the use of such solutions as the construction of rain gardens allows to reduce the probability of overloading of rain or combined sewage infrastructure, partially solving the problem of urban rainwater management (Wanitchayapaisit et al., 2022).

The design of rain gardens is based on the parameters and requirements associated with the specified functions. At the same time, their structure is determined in detail and the appropriate calculation method is chosen, aimed at ensuring optimal parameters, such as size and depth. One of the main methods of such calculations is numerical modelling, whose approaches remain the most widely used tool that allows you to support and improve the processes of planning, design and management in the direction of the concept of sustainable development.

Modelling is a key tool for rain garden research, as it makes it possible to predict and analyse the hydrological characteristics and water quality in systems under different operating conditions (Zhang, Lu, Ding, Peng & Yao, 2018; Wang, Zhang, Babovic & Gin, 2019). In addition, this approach allows you to develop several operational scenarios and obtain important data to improve the efficiency of rain gardens, which is not always possible to provide with experimental methods.

Calculating the optimal design area of a rain garden as part of a sponge system is critical to making effective decisions in urban stormwater management. According to the characteristics of rain gardens, the most common approach in many countries is the infiltration method based on Darcy's law, which is used to calculate the area of the garden (Li, Xiang, Che, & Ge, 2008). This method is based on an assessment of the infiltration capacity of soils but has limitations because it does not consider the influence of the structural features of the location of the rain garden and the role of plants in improving water permeability and cleaning runoff.

In addition to the above-mentioned method, there are two more common approaches: the method of calculating the effective volume of the surface retention layer of rain gardens proposed by Davis and McCuen (2005), and the method of estimating proportions based on the size of the catchment area, which was described in the manual for designing structures for stormwater treatment (Auckland Regional Council, 2003).

The method of calculating the effective volume of the surface retaining layer is based on the water balance equation and uses the volume of the aquifer to reduce the runoff volume. This approach considers the effect of vegetation on water retention but ignores the infiltration capacity and retention properties of the rain garden, which are important for treating the first flush of runoff, which is about 12 mm of rainfall. The method of estimating proportions is a more simplified approach and consists of calculating the catchment area multiplied by the proportionality factor. However, the accuracy of this method is low, and its applicability is limited by the precipitation characteristics and standards for different regions.

The above methods based on Darcy's law have their advantages and limitations. The choice of the appropriate method depends on the analysis of the structural characteristics of the rain garden, its functional purpose, project standards, soil properties and other factors. The infiltration method based on Darcy's law is effective for rain gardens with sandy soil because such soil provides a high infiltration capacity. The method of calculating the effective volume of the surface retention layer is better suited for systems with clay soils and large areas, where water retention on the surface plays an important role. The proportional estimation method is usually used for calculations with known rain garden parameters and is more applicable in cases where the catchment area and other system parameters are well defined.

The universal hydrological infiltration model developed by the authors, based on Darcy's law and Bernoulli's equation, is important, as it makes it possible to describe dynamic processes in the construction of a rain garden (Kravchenko et al., 2024b). Later, this model was improved to consider the height of the water column on the surface of the structure, which made it possible to more accurately model the dynamics of storm runoff and improve the prediction of the hydrological efficiency of the system. This improvement provided a better adaptation of the model to the real conditions of rain garden operation.

In addition to the use of known models, it is important to apply methods of quantitative assessment of the hydrological efficiency of rain gardens. These methods enable the precise determination of key parameters such as water storage volume, infiltration rate, peak flow reduction and runoff retention, and pollutant reduction by the rain garden design during a rainfall event.

The purpose of this study is to model the design parameters of a rain garden and develop methods for quantifying its hydrological efficiency for stormwater management and ensuring widespread use in urban settings.

MODELLING THE RAIN GARDEN'S DESIGN PARAMETERS

The calculation of the effective area of the rain garden must consider infiltration processes, the effect of vegetation on the aquifer, the volume of the storage tank and other factors. To ensure the maximum efficiency of the water-holding capacity of the rain garden, it is assumed that the coefficient of water permeability is $K \geq 1 \cdot 10^{-5} \text{ m} \cdot \text{s}^{-1}$. At the same time, the rainwater flow from impermeable surfaces is directed to the rain garden, which consists of several layers: vegetation cover, a layer of soil mixture for planting plants, an infiltration (sand) layer, and a gravel layer (Fig. 1).

By the time the storm runoff exceeds the storage and infiltration capacity of the rain garden and the water begins to go beyond the calculation area (Fig. 2), a balance is established between the main hydrological elements of the system. This balance can be described using the water balance equation, which considers the volume of water inflow, storage, infiltration and outflow:

$$V + V_1 = X + Y + Z + V_2 + W_1, \quad (1)$$

where:

- V – volume of rainwater collected in the construction of the rain garden during the calculation periods [m^3],
- V_1 – volume of runoff accumulated by the rain garden at the beginning of the calculation periods [m^3],
- X – volume of infiltrated rainwater for the calculation periods [m^3],
- Y – volume of evaporation from the rain garden during the calculation periods [m^3],
- Z – volume of rainwater that saturates the layer of the loose soil mixture for the calculation periods [m^3],
- V_2 – volume of rainwater retained by the rain garden structure at the end of the calculation periods [m^3],
- W_1 – volume of rainwater overflow during the calculation periods [m^3].

When designing the construction of a rain garden, the volume of rainwater overflow W_1 can be taken as zero. If it is assumed that there is no water in the rain garden structure at the beginning of the calculation period ($V_1 = 0$), and the volume of water from the beginning to the end of the period is V_{basin} , then, considering the equality of $V_{\text{basin}} = V_2 - V_1$, it is possible to write $V_{\text{basin}} = V_2$. Accordingly, Formula (1) takes the following form:

$$V = X + Z + V_{\text{basin}}. \quad (2)$$

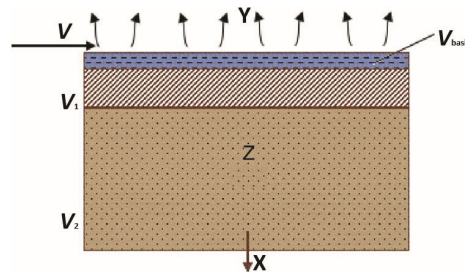


Fig. 2. Scheme used to determine the area of the rain garden structure

Source: own work.

The amount of precipitation per unit area of the rain garden R_Y [$\text{m}^3 \cdot \text{m}^{-2}$] during the calculation periods can be determined by considering the intensity of the precipitation $q(T)$ for the corresponding climatic region. For this, it is necessary to integrate Formula (2), which gives:

$$R_Y = \int_0^\tau q(T) dT, \quad (3)$$

where:

τ – calculation period [min],
 T – duration of rainfall [min].

The volume of rainwater collected in the construction of the rain garden for the calculation periods is calculated according to Formula (4):

$$V = A_{\text{basin}} \cdot R_Y \cdot \varphi \cdot 10^{-4}, \quad (4)$$

where:

A_{basin} – area of the rain garden catchment basin [m^2],
 φ – flow coefficient.

The calculation of the volume of infiltrated rainwater for the calculation period can be expressed using Formula (5):

$$X = \frac{K \cdot (h_{\text{sponge}} + h) \cdot A_{\text{sponge}} \cdot \tau \cdot 60}{h_{\text{sponge}}}, \quad (5)$$

where:

K – water permeability coefficient of the soil mixture layer for planting plants [$\text{m} \cdot \text{s}^{-1}$],
 h_{sponge} – depth of the rain garden [m],
 h – submerged zone forming of the height of the water column [m],
 A_{sponge} – area of the rain garden as a sponge [m^2],
 τ – calculation period [min].

According to the design features of the rain garden and various physical and chemical properties of the soil environment, the value of K entered in Formula (5) can be described based on the following three conditions:

1. Provided that the design of the rain garden includes a layer of an impermeable geotextile membrane or the permeability coefficient of the infiltration layer K_2 is significantly less than the water permeability coefficient of the soil mixture for planting plants K_1 , i.e. $K_2 \ll K_1$ (under other conditions, preferably, $K_2 > K_1$), K_2 can be considered a limiting factor and the volume of infiltrated rainwater X can be neglected, i.e. $X = 0$.
2. Provided that the design of the rain garden includes a drainage system for collecting and draining rainwater or $K_2 \gg K_1$, it can be assumed that $K = K_1$. Provided that $K_2 < K_1$, it can be assumed that $K = K_2$.
3. If the volume of runoff in a rain garden structure exceeds the volume of infiltrated water absorbed by the layers of the structure during the same period, excess stormwater inevitably remains in the system. Suppose that the height of the vegetation cover exceeds the height of the layer forming the water column; in this case, the calculation of the actual volume V_{basin} is determined using Formula (6):

$$V_{\text{basin}} = A_{\text{sponge}} \cdot h_{\text{max}} \cdot (1 - f_v) \cdot 10^{-3}, \quad (6)$$

where:

h_{max} – maximum depth of the immersion zone for the structure of the water column,

f_v – percentage of the cross-sectional area of the vegetation cover from the surface area of the layer for the structure of the water column, which is usually equal to 20%.

The volume of rainwater that saturates the depth of the soil mixture for the calculation periods is determined as:

$$Z = n \cdot A_{\text{sponge}} \cdot h_{\text{sponge}}, \quad (7)$$

where:

n – average porosity of the layer of the soil mixture for planting plants and the infiltration layer, which is taken for calculation as 0.3.

Considering the above formulas, the calculation of the area of the rain garden as an element of the spongy system can be expressed using Formula (8):

$$A_{\text{sponge}} = \frac{A_{\text{basin}} \cdot R_y \cdot \varphi \cdot h_{\text{sponge}}}{60 \cdot K \cdot \tau(h_{\text{sponge}} + h) + h_{\text{max}} \cdot (1 - f_v) \cdot h_{\text{sponge}} + n \cdot h_{\text{sponge}}^2}. \quad (8)$$

Under the condition that $X = 0$, i.e. $K = 0$, Formula (8) can be changed to:

$$A_{\text{sponge}} = \frac{A_{\text{basin}} \cdot R_y \cdot \varphi}{h_{\text{max}} \cdot (1 - f_v) + n \cdot h_{\text{sponge}}}. \quad (9)$$

The proposed method for calculating the area of a rain garden structure is designed to analyse a single rain event under the condition that there is no overflow or water leakage from the structure. The method is also recommended for calculating the effective area of a rain garden in situations where treated rainwater is stored in a tank for reuse. It is important to note that rain gardens are designed for regular rainfall and not for individual extreme events, so the average local rainfall characteristics should be considered when determining the effective area.

Calculating the effective area of a rain garden design is critical for the optimal functioning of such systems in stormwater management, as Figure 3 clearly illustrates.

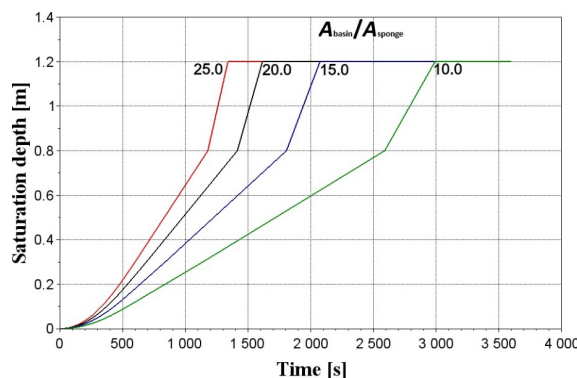


Fig. 3. Curves of the efficiency of the rain garden design without considering the height of the water column depending on its area

Source: own work.

As shown in Figure 3, the maximum efficiency of the rain garden is achieved when the area ratio ($A_{\text{basin}}/A_{\text{sponge}} = 10$). This means that for a 100 m² catchment area, a 10 m² rain garden will be completely filled with water within 50 min of a rain event. As the area of the rain garden decreases, the hydrological efficiency of the structure decreases. For example, in the case of an area ratio equal to 25, that is, with a rain garden area of 4 m², the system is filled in 26 min.

When modelling rain gardens, it is necessary to consider the parameter of the height of the water column, since it significantly affects the dynamics of hydrological processes in the system. Models that consider the height of the water column on the surface of the rain garden are designed mainly to predict the behaviour of the system under conditions of high rainfall intensity (from 25 mm·h⁻¹ and more).

Modelling of hydrological processes in rain gardens with the same design parameters and conditions, but with and without the height of the water column, shows a significant difference in results. The addition of this parameter significantly improves the accuracy of predicting and describing the behaviour of the system during storm events, which is clearly illustrated by the results shown in Figure 4.

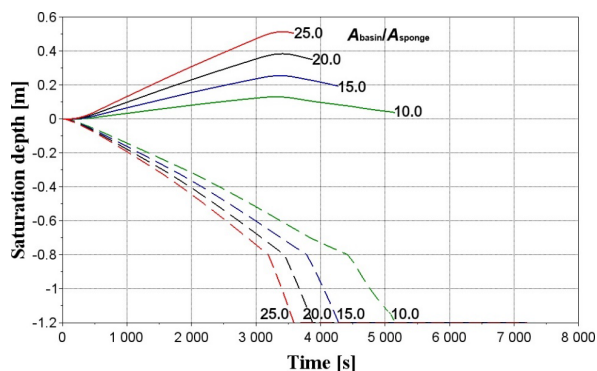


Fig. 4. Efficiency curves of the rain garden design considering the height of the water column depending on its area

Source: own work.

In contrast to the results that do not consider the height of the water column, simulations with an area ratio of $(A_{\text{basin}}/A_{\text{sponge}}) = 10$ show that a 10 m² rain garden will completely fill with water in 1 h and 25 min during a rain event, creating a water column of 0.15 m. With an area ratio of 25, that is, for a rain garden with an area of 4 m², the system will fill in 1 h, and the height of the water column on the surface will reach 0.5 m.

The rain garden design serves three key functions in stormwater management – reducing in stormwater runoff volume, reducing peak runoff velocity, and reducing in total water pollutants – therefore, a quantitative assessment method for these functions was proposed.

Method of assessing the reduction of the volume of storm runoff by the construction of a rain garden

Let us assume that the estimated recurrence period of a certain rain event is N_1 , and the corresponding amount of precipitation is R [mm]. The recurrence period N_1 is the time interval, expressed in years, during which a certain rainfall event is expected to recur with the same amount of precipitation or an excess of precipitation intensity compared to the previous event.

The curve showing the change in the intensity of rain runoff depending on the flow of rainwater Q [m³·s⁻¹] and the duration of precipitation T [min] is presented in Figure 5.

Taking the corresponding area of the rain garden as A_{sponge1} and the volume of water retained by the rain garden as U_1 , according to formula (1), the water balance equation can be written as $U_1 = X + V_{\text{basin}} + Z$. The value of X can be neglected if a layer of waterproof membrane is placed on the bottom of the rain garden structure or provided that $K_2 \ll K_1$.

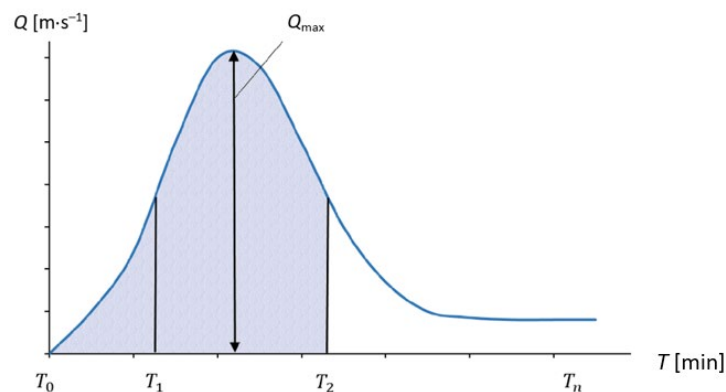


Fig. 5. Curve of changes in the intensity of storm runoff

Source: own work.

Under the condition that the period of repetition of the rain event is $N \geq N_1$, it can be assumed that $U' = U_1$. Otherwise, under the condition that the repetition period is $N \leq N_1$, it can be assumed that $U' = U$. The coefficient of reduction of the volume of storm runoff can also be written as a ratio:

$$\eta = \frac{U'}{U} \cdot 100\%. \quad (10)$$

where:

U' – volume of runoff retained by the structure of the rain garden [m³],

U – output flow volume [m³].

Method of estimating the reduction of the annual flow volume

This method is based on the calculation of the daily amount of precipitation. Let us assume that the calculated amount of precipitation is R [mm]. According to the data of climate observations and long-term precipitation statistics, the following parameters can be determined: the amount of precipitation n per year; the amount of precipitation exceeding or equal to R was a ; the amount of precipitation less than R was b , then $n = a + b$, and the corresponding amount of precipitation for each rain event is R_i ($i = 1, 2, \dots, n$).

If there is no data on the amount of precipitation in a certain climatic area, this information can be obtained from the data on the daily amount of precipitation, which, for example in Ukraine, is updated on the Boris Sresnevsky Central Geophysical Observatory website. Then, the annual flow reduction volume and the annual flow reduction coefficient are represented in Formulas (11) and (12) as:

$$U'' = a \cdot \varphi \cdot R \cdot A_{\text{basin}} + \sum_{i=1}^b \varphi \cdot R_i \cdot A_{\text{basin}}, \quad (11)$$

$$\eta' = \frac{U''}{\sum_{i=1}^n \varphi \cdot R_i \cdot A_{\text{basin}}} \cdot 100\% = \frac{a \cdot R + \sum_{i=1}^b R_i}{\sum_{i=1}^n R_i} \cdot 100\%, \quad (12)$$

where:

U'' – annual volume of storm runoff reduction [m^3],

η' – coefficient of annual flow reduction.

Method of estimating the reduction of peak runoff volume by the construction of a rain garden

Considering the volume of water retained by the rain garden and the volume of peak runoff, the curve that describes the process of reducing the peak water runoff during a rain event is presented in Figure 6.

The volume of water retained by the rain garden U_1 can be written as:

$$U_1 = \varphi \cdot A_{\text{basin}} \cdot \int_{T_0}^{T_n} q(T) dT, \quad (13)$$

where:

T_0 – start time of storm runoff formation [min],

T_n – flow duration [min].

The runoff volume, which depends on the volume of water retained by the rain garden structure, corresponds to the size of the shaded area as shown in Figure 4. Then the peak runoff volume corresponding to time T_2 and the corresponding peak runoff reduction factor are described by Formulas (14) and (15):

$$Q' = Q_{\text{max}} - U_1. \quad (14)$$

$$\theta = \frac{Q_{\text{max}} - Q}{Q_{\text{max}}}, \quad (15)$$

where:

Q' – volume of retained peak flow [m^3],

Q_{max} – maximum peak flow volume [m^3],

U_1 – volume of water retained by the rain garden [m^3],

θ – reduction factor of the peak flow level.

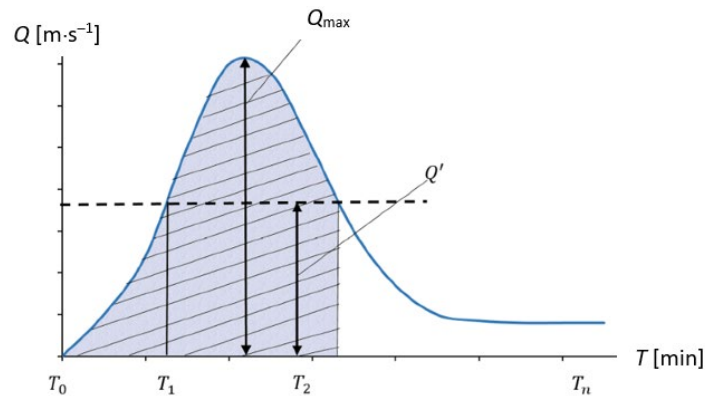


Fig. 6. Curve of reduction of peak water flow during a rain event

Source: own work.

Method of assessing the reduction of the total amount of pollutants by the construction of a rain garden

Let us denote the change in the intensity and concentration of stormwater pollutants over time through the parameters $q(T)$ and $C(T)$, and the concentration decreases with the increasing time. Depending on the structure and design features of the rain garden, the overall reduction of pollutants can be considered in two cases.

Method for assessing pollutant reduction by rain garden construction during a single rain event

First case. If the rain garden design includes a drainage system of impervious and non-perforated collector pipes that are installed in a layer of gravel, this means that the runoff that enters the rain garden is collected inside the structure. In this case, it can be assumed that the pollutants are fully removed by the rain garden structure in full, which can be described as:

$$m = M - U' \cdot C_r, \quad (16)$$

$$\varepsilon = \frac{m}{M} \cdot 100\%, \quad (17)$$

where:

m – total amount of pollutants removed by the rain garden construction [mg],

M – total amount of pollutants entering the rain garden structure [mg],

U' – volume of water retained by the rain garden [m³],

C_r – average concentration of pollutants in the water of one rain event [mg·dm⁻³],

ε – overall coefficient of reduction of pollutants in stormwater runoff.

The average concentration of pollutants in the water of one rain event can be calculated based on Equation (18):

$$C_r = \frac{M}{U} = \frac{\int_{T_0}^{T_n} C(T) \cdot q(T) dT}{q(T) dT} = \frac{\sum C(T) \cdot q(T) \Delta T}{\sum q(T) \Delta T}, \quad (18)$$

where:

U – total volume of initial rain runoff [m^3],

T_0 – start time of flow formation [min],

T_n – flow duration [min],

ΔT – sampling interval time (time between successive measurements or sampling) [min].

Then, considering Formula (13), the total amount of pollutants removed by the construction of the rain garden can be determined:

$$m = \varphi \cdot A_{\text{basin}} \cdot C_r \cdot \int_{T_0}^{T_n} q(T) dT. \quad (19)$$

Second case. If the rain garden design includes a permeable layer and a drainage system of perforated pipes in the bottom layer of gravel is present, then it can be assumed that the pollutants are partially removed by the rain garden design.

Then:

$$M = m - U' \cdot C_r, \quad (20)$$

$$\varepsilon = \frac{m}{M} \cdot 100\%, \quad (21)$$

where:

C – average concentration of pollutants in the effluent at the exit from the rain garden structure [$\text{mg} \cdot \text{dm}^{-3}$].

Method of assessing the annual reduction of pollutants by the construction of a rain garden

For the first case, the total annual amount of pollutants removed and the coefficient of reduction of their total amount are shown in the form of Formulas (22) and (23):

$$M' = (a \cdot \varphi \cdot R \cdot A_{\text{basin}} + \sum_{i=1}^b \varphi \cdot R_i \cdot A_{\text{basin}}) \cdot C_1, \quad (22)$$

$$\varepsilon' = \frac{M'}{\sum_{i=1}^n \varphi \cdot R_i \cdot A_{\text{basin}} \cdot C_1} \cdot 100\% = \frac{a \cdot R + \sum_{i=1}^b R_i}{\sum_{i=1}^n R_i} \cdot 100\%, \quad (23)$$

where:

M' – total annual amount of pollutants removed [mg],

C_1 – average concentration of pollutants in the runoff for n cases of rain events [$\text{mg} \cdot \text{dm}^{-3}$],

ε' – coefficient of reduction of the total amount of pollutants.

For the second case, the total annual amount of pollutants removed and the coefficient of reduction of their total amount are shown in the form of Formulas (24) and (25):

$$M'' = (a \cdot \varphi \cdot R \cdot A_{\text{basin}} + \sum_{i=1}^b \varphi \cdot R_i \cdot A_{\text{basin}}) \cdot (C_1 - C'), \quad (24)$$

$$\varepsilon' = \frac{M''}{\sum_{i=1}^n \varphi \cdot R_i \cdot A_{\text{basin}} \cdot C_1} \cdot 100\% = \frac{(a \cdot R + \sum_{i=1}^b R_i) \cdot (C_1 - C')}{\sum_{i=1}^n R_i \cdot C_1} \cdot 100\%, \quad (25)$$

where:

C' – average concentration of pollutants in the runoff for n cases of rain events [$\text{mg} \cdot \text{dm}^{-3}$].

CONCLUSIONS

Rain gardens are widely used for stormwater management in small catchment areas, playing a key role in reducing peak runoff rates, wastewater volume and overall pollution, and protecting water resources. Although there are many models in the scientific literature describing the hydrological parameters of rain gardens, an important aspect that remains understudied is the detailed consideration of the main hydrological elements of the water balance. A numerical model has been developed that makes it possible to calculate of the effective area of a rain garden structure for a single rainfall event, provided that the structure does not overflow or leak. Methods of assessing three key functions of rain gardens in the field of stormwater management are proposed: a method of assessing the reduction of the volume of stormwater runoff; a method of estimating the reduction of the annual flow volume; a method of estimating the reduction of the peak flow volume; and a method of assessing the reduction of the total amount of pollutants.

These numerical models can be a useful tool in the planning and implementation stages of rain garden investments, especially in urban areas, enabling more efficient stormwater management. In further studies, it is planned to validate the developed methodology by comparing the simulation results with the data of field observations and experimental measurements. This will allow us to assess the accuracy and reliability of the calculation methods, and to clarify and improve the existing models considering the real conditions of operation of rain gardens. This validation will include an analysis of different scenarios of rain events and types of rain gardens, which will allow more accurate prediction of their hydrological performance and optimisation of their design and implementation in the urban environment.

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Authors’ contributions

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

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ILOŚCIOWA OCENA EFEKTYWNOŚCI HYDROLOGICZNEJ PROJEKTU OGRODU DESZCZOWEGO W KONTEKŚCIE ZARZĄDZANIA OBJĘTOŚCIĄ I JAKOŚCIĄ ŚCIEKÓW DESZCZOWYCH

STRESZCZENIE

Ogrody deszczowe są popularnym elementem zielonej infrastruktury, często integrowanym z koncepcją miasta-gąbki w celu rozwiązania problemów związanych z zarządzaniem wodami opadowymi. Takie konstrukcje spełniają trzy główne funkcje: zmniejszają objętość spływu wody z obszaru zlewni, zmniejszają przepływy szczytowe w systemie odwodnienia (co jest krytyczne dla zapobiegania przeciążeniu sieci kanalizacyjnej) oraz poprawiają jakość wody (co przyczynia się do zachowania wód gruntowych). Projektowanie ogrodów deszczowych polega na spełnieniu konkretnych wymagań i uwzględnieniu cech, które determinują ich konstrukcję i metody obliczeniowe w celu uzyskania optymalnych parametrów takich jak powierzchnia i głębokość. Analiza scjentometryczna pokazuje, że znaczący wkład badawczy wnoszą różne kraje, ale większość istniejących systemów ogrodów deszczowych polega na ogólnych zaleceniach, co może prowadzić do problemów w działaniu. Celem pracy jest opracowanie modelu obliczania głównych parametrów ogrodów deszczowych i metod oceny ich wydajności hydrologicznej w celu poprawy wdrażania tych systemów w środowisku miejskim. Przedstawiono model numeryczny do obliczania efektywnej powierzchni ogrodu deszczowego, który uwzględnia jedno zdarzenie deszczowe i wyklucza przelew. Zaproponowano metody oceny trzech kluczowych funkcji ogrodów deszczowych w kontekście zarządzania wodami opadowymi: metodę określania redukcji odpływu powierzchniowego, metodę szacowania rocznej redukcji odpływu powierzchniowego, metodę redukcji szczytowego odpływu powierzchniowego oraz metodę szacowania całkowitej redukcji zanieczyszczeń.

Słowa kluczowe: ogród deszczowy, odwodnienia burzowe, zarządzanie wodami opadowymi, modelowanie, parametry ogrodu deszczowego

SEEPAGE ANALYSIS OF THE MAMAK DAM, INDONESIA: A CASE STUDY

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ABSTRACT

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. However, the presence of leakage on the downstream slope has become an issue that requires attention. This study analyses seepage using GeoStudio and Slide Rocscience software. The seepage rates obtained from instrument readings exceed those calculated by GeoStudio and Slide Rocscience software. All of the obtained seepage rate results do not surpass the maximum allowable seepage rate requirements. The most critical gradients are from flood water level cases in Saddle Dam-1 and Saddle Dam-2. They reached values of 0.35 and 0.34, which fall below the maximum hydraulic gradient.

Keywords: seepage rate, instrument readings, hydraulic gradient

INTRODUCTION

Dams pose a high level of danger to both human lives and property in the event of structural damage or breaches in their structures (Sujono, 2012). Samekto and Azdan (2008) suggest that failures in dams can occur due to various factors (Utepov et al., 2022). Primary causes of dam failure include water overflow (overtopping), water leakage, landslides (dam stability) and other factors such as earthquakes, liquefaction or sabotage according to the International Commission on Large Dams (ICOLD, 2018, 2019). Among these causes, water seepage is the most frequent accounting for 43% of dam failures. When a dam structure fails, it is often due to water leaking, leading to serious problems and potential disasters.

One of the leading causes of embankment dam failure is water leakage, leading to a process known as “piping”, which disrupts the dam’s stability and safety. To prevent hazardous water leakage, monitoring and assessing dam leakage condition is essential. This is typically done using instruments like piezometers placed on the dam’s body and drainage systems (v-notch) installed downstream as a toe drain (Foster, Fell & Spannagle, 2000).

The amount of water leakage is influenced by factors such as material permeability coefficient (k), hydraulic gradient (i) and water level in the reservoir (Δh), (Wulandari & Tjandra, 2019).

Water leakage increases as the pressure on the dam rises, and the time for water to seep through shortens (Nurnawaty, Suhardiman & Ihwan, 2018). Rising water levels in the reservoir elevate pressure inside the dam’s pores, causing more water leakage (Huda, Wardani & Suharyanto, 2019). Variations in water levels

impact the pressure within the dam's pores. Rainfall intensity influences the pore water pressure on the dam's upstream slope, with heavier rainfall resulting in more significant variations in pressure (Huda et al., 2019).

The Indonesian Dam Safety Commission's study 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 aim of the paper is to analyse the behaviour of the Mamak Earth Dam in Indonesia by assessing the filtration process in complex geological, geotechnical and seismic conditions. The basics of analysing the filtration process through earth dams are presented, considering the impacts, flow conditions and filtration safety criteria. The filtration process through the main dam, saddle dams and abutments was evaluated based on the results of numerical analysis using GeoStudio and Slide Rocscience software to determine seepage rates and hydraulic gradients. These results were then compared with the available measurements from the control system.

LITERATURE REVIEW

Theory of seepage

Due to changes in pressure and elevation, groundwater moves towards areas of lower potential energy. The total head, commonly used to quantify potential energy (UE), is essentially the combined value of pressure head and elevation head. The differential form of Darcy's law indicates that the flow rate per unit area is directly proportional to the rate at which the head changes. The subsequent fundamental equation governing seepage through earth dams can be regarded as (Elshemy, Nasr, Bahloul & Rashwan, 2002; Ismail, Ng & Gey, 2012):

$$\frac{\partial}{\partial x} \left[k_x \frac{\partial H}{\partial x} \right] + \frac{\partial}{\partial y} \left[k_y \frac{\partial H}{\partial y} \right] + \frac{\partial}{\partial z} \left[k_z \frac{\partial H}{\partial z} \right] = S \frac{\partial h}{\partial t}, \quad (1)$$

where:

k_x, k_y, k_z – coefficients of permeability in x, y and z directions, respectively [-],

S – specific yield [-],

H – total fluid head ($H = p/\gamma_w + z$) [m],

p – pressure [Pa],

γ_w – unit weight of water [$\text{kN} \cdot \text{m}^{-3}$],

z – elevation head [m].

Equation (1) is commonly referred to as Laplace's equation, serving as the fundamental equation for modelling three-dimensional groundwater flow in aquifers. When considering a steady-state scenario in an isotropic and homogeneous aquifer, Equation (2) can be simplified to the following expression:

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial z^2} = 0. \quad (2)$$

The assumptions made are as follows: the soil media is homogeneous, isotropic and physically stable; atmospheric pressure prevails throughout the water table (phreatic surface); the flow of groundwater through the flow domain is steady and the hydraulic conductivity within the embankment remains constant throughout.

This study uses Seep/W function of GeoStudio software to model water seepage from a reservoir through an earth dam while calculating the factor of safety (FoS) against slope failure using the simplified

Bishop's method and considering various soil conditions. The fundamental differential equation that governs two-dimensional seepage can be formulated as follows:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) + Q = \frac{\partial \theta}{\partial t}, \quad (3)$$

where:

Q – flow rate [$\text{m}^3 \cdot \text{s}^{-1}$],

θ – water content volume [m^3].

Equation (3) illustrates that the disparity between the inflow and outflow rates corresponds to the alteration in the storage of soil systems.

There are two fundamental categories of seepage analysis: steady-state seepage, which models the behaviour of reservoir water when it is at full storage; and transient-state seepage, which simulates the drawdown of reservoir water (Himanshu & Burman, 2019). The mathematical expressions associated with each type are as follows:

– for steady-state seepage:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) + Q = 0, \quad (4)$$

– for transient-state seepage:

$$\frac{\partial}{\partial x} \left(k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y \frac{\partial H}{\partial y} \right) + Q = m_w \gamma_w \frac{\partial(H)}{\partial t}, \quad (5)$$

where:

H – total available hydraulic head difference [m],

t – time factor [s],

Q – applied boundary flux (discharge) [$\text{m}^3 \cdot \text{s}^{-1}$],

m_w – slope of the storage curve [$^\circ$].

Boundary conditions

Figure 1 is a diagrammatic illustration of the problem statement and boundary conditions for a typical earth dam.

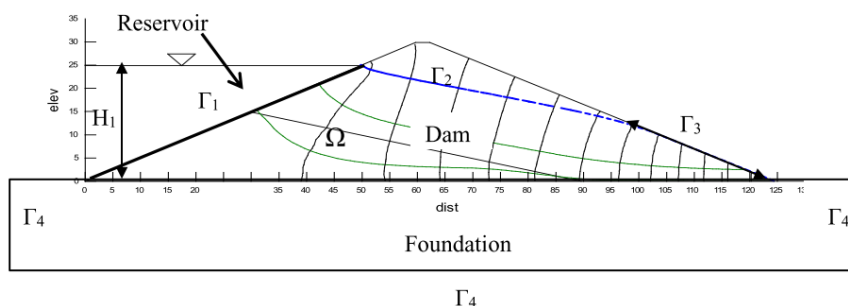


Fig. 1. Problem statement and boundary conditions

Source: Kirra et al. (2015).

These boundary conditions can be briefly summarised as follows:

- Entrance surface ($\Gamma 1$): the upstream boundary surface, denoted as $\Gamma 1$, serves as the entry point where water begins to permeate through the material. This surface is regarded as an equipotential line, referred to one of Dirichlet's condition, specifying a predetermined head:

$$H(x, y) = H_1. \quad (6)$$

- Phreatic surface ($\Gamma 2$): the boundary surface labelled as $\Gamma 2$, representing the path of flow through the dam, corresponds to the phreatic surface. This separation line is seen as a streamline. While the phreatic surface is regarded as a boundary condition, its exact location and shape are initially uncertain. In the case of the unknown phreatic surface, the boundary condition is as follows:

$$H(x, y) = y, \quad (7)$$

$$\frac{\partial H}{\partial n} = 0, \quad (8)$$

where:

n – normal directions to the boundary ($\Gamma 2$).

- Exit surface (seepage surface) ($\Gamma 3$): the boundary surface, denoted as $\Gamma 3$, functions as the exit surface or seepage surface. This boundary is treated as an isobar, where the pressure is atmospheric along its length. Consequently, the boundary condition associated with such a surface is:

$$H(x, y) = y. \quad (9)$$

The configuration of the seepage surface is understood, except for its upper boundary, which is the exit point situated on the unknown phreatic surface. Determining the location of this specific point is essential for finding a solution.

- Dam foundation boundary ($\Gamma 4$): the boundary surface, referred to as $\Gamma 4$, represents the dam's foundation boundary and is associated with the Neumann boundary condition. In this study, this boundary is assumed to be impermeable, meaning it obstructs the flow of water across it. Consequently, the condition is defined as follows:

$$\frac{\partial H}{\partial n} = 0, \quad (10)$$

where:

n – normal direction to the boundary ($\Gamma 4$).

Safety criteria

In the Seep/W function of GeoStudio software, the amount of water that seeps out from the dam body to the downstream area is calculated by multiplying the average seepage water volume with the width of the dam for each metre. According to Indonesian guidelines, the calculation focuses on the cross-section that has the deepest part of the dam using the following equation:

$$Q_h = q_h \cdot A \cdot B, \quad (11)$$

where:

Q_h – seepage flow rate [$\text{m}^3 \cdot \text{s}^{-1}$],

q_h – average water flow [$\text{m}^3 \cdot \text{s}^{-1}$],

A – zone area [m^2],

B – width of the base area of the foundation [m].

The safety criteria of seepage analysis in the dam body is defined as follows:

$$i_c = \frac{\gamma'}{\gamma_w} = \frac{G_s - 1}{1 + e}, \quad (12)$$

$$FoS = \frac{i_c}{i_e} > 4, \quad (13)$$

where:

i_c – critical discharge gradient [-],

γ' – effective unit weight (submerged) [$\text{kN} \cdot \text{m}^{-3}$],

G_s – specific gravity unit weight [-],

e – void ratio [-],

i_e – exit gradient from seepage analysis or instrument measurement data [-],

FoS – factor of safety [-].

The parabolic equation of seepage line is defined by the following equation:

$$y_0 = \sqrt{(h^2 + d^2)} - d. \quad (14)$$

The design aims to manage leakage to an acceptable level. Quies (2002) defined guidance on typical seepage losses from earth dams, which is provided in Table 1.

Table 1. Guidance on typical seepage losses from earth dams

Dam height [m]	Seepage [L/min/m]	
	permissible	impermissible
< 5	< 25 (0.02)	> 50 (0.03)
5–10	< 50 (0.03)	> 100 (0.07)
10–20	< 100 (0.07)	> 200 (0.14)
20–40	< 200 (0.14)	> 400 (0.28)
40 >	< 400 (0.28)	> 800 (0.56)

Source: Quies (2002).

Meanwhile, regarding the hydraulic gradient, according to DIN 19700-12 (Deutsche Institut für Normung [DIN], 2004), as cited in Ersoy and Haselsteiner (2018), the critical gradient (i_c) for the present sand-gravels should be approximately to 0.20–0.40. For fine sands, this can decrease to 0.15, and for silts, it can be as low as 0.10 or even less.

CHARACTERISTICS OF THE MAMAK DAM

The Mamak Dam, constructed in 1990 on Sumbawa Island, Indonesia, has undergone continuous inspections throughout its 30-year operational period to address potential issues and mitigate the risks associated with water seepage, a critical concern for dam safety. This study examines seepage in the Mamak Dam, with a focus on its safety. Monitoring data from instruments such as piezometers and drainage systems (v-notches) are employed to observe water behaviour and compare the analysis results. According to the PT. Raya Konsult (2022b), the first v-notch system accumulates seepage from the main dam, while the second v-notch system accumulates seepage from Saddle Dam-1, measuring the amount of seepage flow on the measured seepage rate is based.

The Mamak Dam serves multiple functions, including hydropower generation, irrigation and local water supply. It has four embankments: the main dam, Saddle Dam-1, Saddle Dam-2 and Saddle Dam-3 (Fig. 2). The structure of Mamak Dam consists of several essential elements, including the impervious core (constructed from earth fill), a filter layer, a transition layer, random rock, selected rock and rock fill. The specifications of the Mamak Dam are provided in Table 2.



Fig. 2. Bird's view of the Mamak Dam

Source: PT. Raya Konsult (2022a).

Table 2. Salient features of the Mamak Dam

Description	Unit measurement	Value
Reservoir		
Catchment area	km ²	108
Gross storage at FWL	million m ³	29.839
Live storage capacity	million m ³	27.671
Dead storage capacity	million m ³	2.167
Water spread area at FWL	km ²	2.357
Flood water level (FWL)	m	elevation +95.40

Table 2 (cont.)

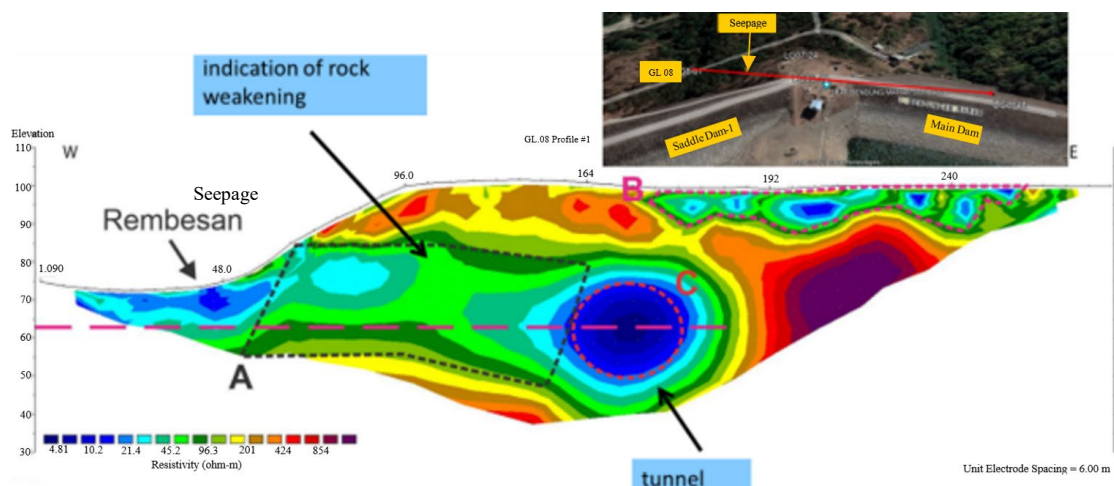
Description	Unit measurement	Value
Normal water level (NWL)	m	elevation +93.43
Low water level (LWL)	m	elevation +74.00
Deepest bed level	m	elevation +58.00
Design flood discharge (probable maximum flood)	m ³ ·s ⁻¹	664 (0.5 PMF)
Main dam + cofferdams		
Height	m	36.959
Crest level	m	elevation +99.93
Length	m	203.01
Crest width	m	10.66
Saddle Dam-1		
Height	m	33.929
Crest level	m	elevation +99.93
Length	m	205.394
Crest width	m	10.245
Saddle Dam-2		
Height	m	10.929
Crest level	m	elevation +99.56
Length	m	54.611
Crest width	m	9.832
Saddle Dam-3		
Height	m	16.538
Crest level	m	elevation +99.80
Length	m	85.986
Crest width	m	10.154

Source: PT. Raya Konsult (2022b).

Seepage in Saddle Dam-1 and Saddle Dam-2

Based on geoelectric investigation, the seepage in Saddle Dam-1 is likely to originate from pockets of water present on the surface of Saddle Dam-1 because there is an indication of low resistivity at the surface. Low resistivity on the surface of the downstream slope indicates rock softening, which affects the permeability of the soil near the seepage point (Fig. 3a). Seepage in Saddle Dam-2 is observed to flow from the deformation zone (Zone C) through the pores of softened rock (northern part of Zone I), then exit through Zone E (seepage). This means there is a water connection pathway from the curved area on the crest to the seepage point on the downstream side. The deflection contributes to the seepage only when Zone C is filled with water (Fig. 3b).

a



b

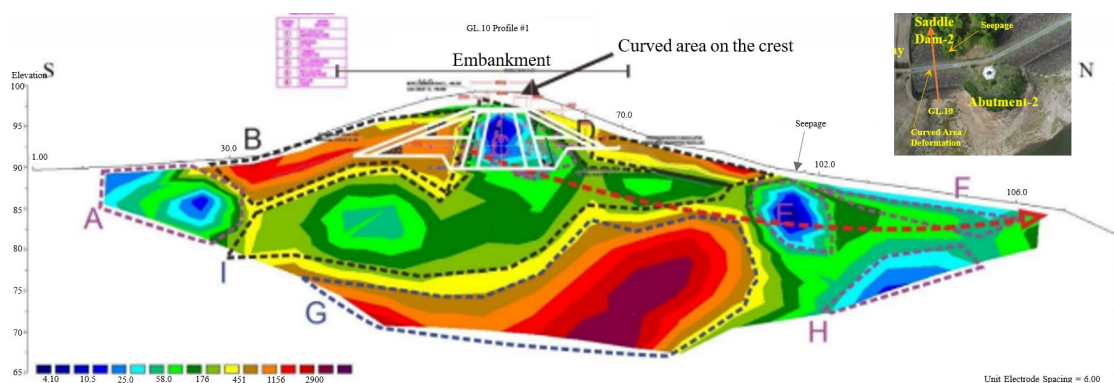


Fig. 3. Geoelectric investigation: a – Geoelectric survey Line 8 (GL8) in Saddle Dam-1, b – geoelectric survey Line 10 (GL10) in Saddle Dam-2

Source: PT. Raya Konsult (2022a).

Geotechnical design parameters

In the process of constructing a numerical model, the next stage involves allocating materials to the regions within it. The key factors for seepage analysis are the geotechnical parameters.

The geotechnical parameters of the main dam, Saddle Dam-1, Saddle Dam-2, Abutment-1 and Abutment-2, which are incorporated in the numerical model, are presented in Table 3. The cross-sections for the analysis are illustrated in Figure 4.

Table 3. Geotechnical parameters of the Mamak Dam

Type	Zone	Soil classification	Saturated permeability coefficient (k_s) [m·s ⁻¹]	Zone area ($A = k_y/k_x$) [-]	Unit weight (γ) [kN·m ⁻³]	Effective cohesion (c') [kPa]	Effective angle of friction (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).

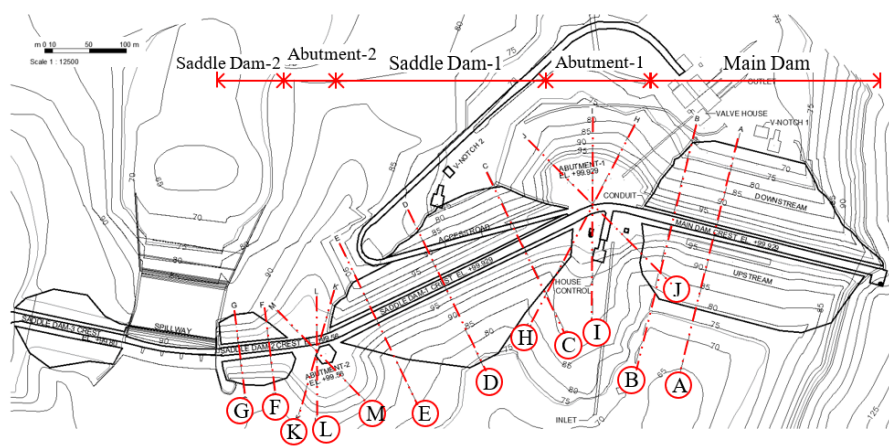


Fig. 4. Location of the cross-sections on the dam plane for seepage analysis

Source: Halim (2023).

To ensure accurate inputs for the numerical model, the geotechnical parameters are incorporated in accordance with construction material data and laboratory test results from soil samples taken in the ground field. To provide a refined set of inputs for the numerical model, the geotechnical parameters are organised based on the designated zones typically found in embankment dams.

Verification model

The assessment of stability is conducted for both the slopes on the upstream and downstream sides of the Mamak Dam embankment. Then, the outcomes of the analysis are compared with the safety standards and guidelines. The view of one of the numerical models (Cross-section A) is given in Figure 5.

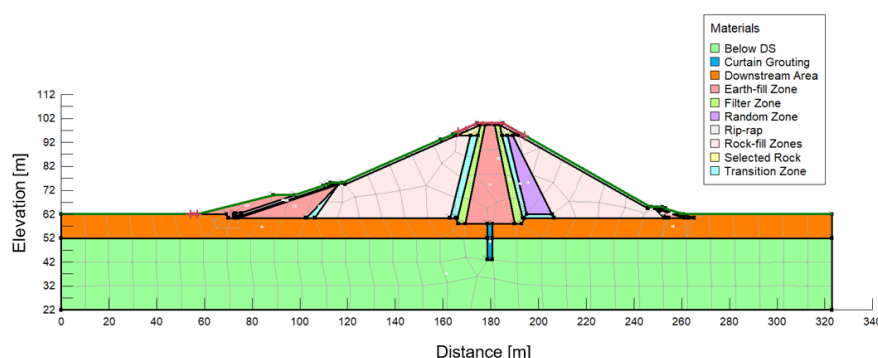


Fig. 5. Finite element model for seepage analysis (Cross-section A)

Source: GEO-SLOPE International (2023).

To investigate seepage flow under stable (steady state) conditions within the embankment, the finite element method (FEM) necessitates the specification of boundary conditions. Three hydraulic boundary conditions are applied for the numerical model as follows:

1. Constant head in the upstream face at a height of 71.2 m (NWL) with 31.2 m above the terrain surface. It can be seen in the pink line in Figure 5.
2. Constant head in the downstream face at the normal water level, which is at a height of 40 m. It can be seen in the yellow downstream line in Figure 5.
3. Seepage exit, which has a total flux type for a boundary. Potential seepage areas exit along the downstream slope have the groundwater flow as $0 \text{ m}^3 \cdot \text{s}^{-1}$. It can be seen in the red line in Figure 5.

ANALYSIS OF RESULTS

Seepage analysis results

In each case, the results from instrument readings report significantly higher seepage rates compared to the results of GeoStudio and Slide Rocscience software. This is due to certain conditions of the materials within the embankment of Saddle Dam-1 and Saddle Dam-2. In Saddle Dam-1, low resistivity on the surface of the downstream slope indicated rock softening, which affects the permeability of the soil near the seepage point. Conversely, Saddle Dam-2 has a water connection pathway from the curved area on the crest to the seepage point on the downstream side, thus causing the seepage rate from instrument readings to be higher than the results of GeoStudio and Slide Rocscience software (Table 4).

Table 4. Seepage rate in the downstream side

Dam part	GeoStudio software			Slide Rocscience software			PT. Raya Konsult (2022)	
	NWL (93.43 m) [m ³ ·s ⁻¹]	FWL (95.40 m) [m ³ ·s ⁻¹]	LWL (74.00 m) [m ³ ·s ⁻¹]	NWL (93.43 m) [m ³ ·s ⁻¹]	FWL (95.40 m) [m ³ ·s ⁻¹]	LWL (74.00 m) [m ³ ·s ⁻¹]	elevation 94.25 m [m ³ ·s ⁻¹]	elevation 93.58 m [m ³ ·s ⁻¹]
Main dam	7.03E-06	7.92E-06	3.31E-07	2.55E-07	2.57E-07	2.08E-07	3.28E-04 ^a	–
Saddle Dam-1	1.44E-06	1.61E-06	1.13E-07	5.79E-07	6.02E-07	4.63E-07	2.62E-04 ^a	1.90E-05 ^b
Saddle Dam-2	8.85E-08	2.63E-07	–	4.63E-07	5.79E-07	–	–	2.60E-05 ^b
Abutment-1	3.13E-05	3.03E-05	2.32E-05	5.56E-07	5.80E-07	4.40E-07	–	–
Abutment-2	7.01E-04	8.48E-04	–	6.02E-07	1.74E-07	–	–	–

NWL – normal water level, FWL – full water level, LWL – low water level.

^aSeepage rate measured from v-notch.

^bSeepage discharge was collected into a measuring cylinder through a pipeline from where the rate of seepage was calculated.

Source: Halim (2023).

However, each seepage rate has satisfied the requirement. In conclusion, the seepage that occurred in the Mamak Dam is considered to be safe. However, the presence of water seepage on the upstream slope creates a problem that requires local protection using a composite geosynthetic barrier and continuous observations.

Hydraulic gradient

The hydraulic gradients within the dam body are generally safe, $0.20 < i_c < 0.40$. The most critical gradients are from flood water level cases in Saddle Dam-1 and Saddle Dam-2, 0.35 and 0.34, respectively (Table 5). Thus, erosion through the dam body should not be a problem, except for Saddle Dam-2, where there is a water connection pathway from the curved area on the crest to the seepage point on the downstream side.

Table 5. Hydraulic and critical gradients

Dam part	Exit gradient (i_e) from GeoStudio [m ³ ·s ⁻¹]			Exit gradient (i_e) from Slide Rocscience [m ³ ·s ⁻¹]		
	NWL	FWL	LWL	NWL	FWL	LWL
Main dam	0.28	0.30	0.28	0.31	0.32	0.28
Saddle Dam-1	0.30	0.33	0.11	0.34	0.35	0.21
Saddle Dam-2	0.13	0.20	–	0.25	0.34	–
Abutment-1	0.27	0.33	0.13	0.17	0.30	0.15
Abutment-2	0.29	0.35	–	0.26	0.35	–

NWL – normal water level, FWL – full water level, LWL – low water level.

Source: Halim (2023).

This condition could potentially lead to the failure of the embankment in Saddle Dam-2. Therefore, it is necessary to address and reduce the risk of unforeseen hazards by installing a water-resistant barrier (a geocomposite consisting of a layer of natural sodium bentonite clay sandwiched between two geotextile layers (non-woven geotextile) or geomembrane (HDPE geomembrane) – Figure 6.

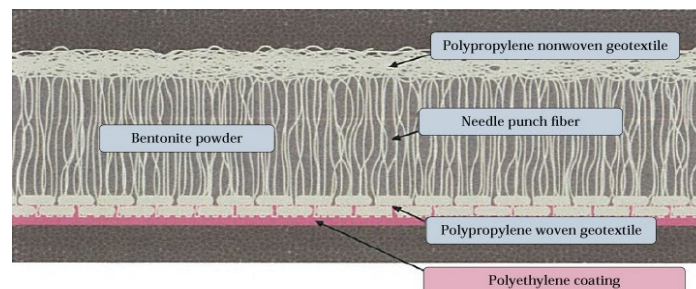


Fig. 6. Structural composition of geocomposite

Source: Koerner (2012).

The bentonite clay in GCLs has excellent swelling and self-sealing properties. When hydrated, the clay swells to create a watertight barrier and can self-heal if punctured. This makes GCLs an effective choice for reducing or eliminating local seepage in these applications.

CONCLUSIONS

The following conclusions have been drawn from the presented work:

- The seepage rates obtained from instrument readings exceed those calculated by the GeoStudio and Slide Rocscience analyses. This is due to certain condition of the materials within the embankment of Saddle Dam-1 and Saddle Dam-2. In Saddle Dam-1, low resistivity on the surface of the downstream slope indicated rock softening, which affects the permeability of the soil near the seepage point. On the other hand, Saddle Dam-2 has a water connection pathway from the curved area on the crest to the seepage point on the downstream side. These conditions should be modelled in the GeoStudio and Slide Rocscience numerical simulation to obtain more localised and accurate results. Nevertheless, each seepage rate result has satisfied the requirement. Therefore, the seepage problem in Saddle Dam-1 and Saddle Dam-2 is considered to be safe.
- The most critical gradients (i_c) come from flood water level cases in Saddle Dam-1 and Saddle Dam-2, where they are 0.35 and 0.34, respectively. However, the hydraulic gradients within the dam body were generally found to be safe as the required hydraulic gradient is $0.20 < i_c < 0.40$. Thus, erosion through the dam body should not be a problem, except for Saddle Dam-2 because of certain conditions within the dam body. This condition could potentially lead to the failure of the embankment in Saddle Dam-2. Therefore, it is necessary to address and reduce the risk of unforeseen hazards.
- To prevent the higher value of hydraulic gradients from being strong enough to continue the erosion process through the embankment and cause failure, it is suggested to install a water-resistant barrier/geocomposite consisting of non-woven geotextile, HDPE geomembrane and geosynthetic clay liner. The water-resistant barrier or geocomposite is positioned on the upstream slopes of both Saddle Dam-1 and Saddle Dam-2, as well as on the upstream slope of Abutment-1 and Abutment-2.

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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.

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ANALIZA FILTRACJI PRZESZ ZAPORĘ MAMAK, INDONEZJA: STUDIUM PRZYPADKU

STRESZCZENIE

Ogólna ocena bieżącego stanu technicznego zapory Mamak wpisuje się w kategorię „akceptowalny” nawet po trzęsieniu ziemi o magnitudzie 6,5 Mw w 2018 roku. W artykule przeanalizowano reakcje zapory ziemnej Mamak w Indonezji pod kątem oceny przebiegu procesu filtracji w złożonych warunkach geologicznych, geotechnicznych i sejsmicznych. Przedstawiono podstawy analizy procesu filtracji przez zapory ziemne z uwzględnieniem występujących oddziaływań, warunków przepływu i kryteriów bezpieczeństwa filtracyjnego. Analizę procesu filtracji przeprowadzono z wykorzystaniem programów GeoStudio i Slide Rocscience. Prędkości przepływu uzyskane z odczytów instrumentów przekraczają obliczone z programów GeoStudio i Slide Rocscience. Wszystkie uzyskane wartości prędkości przepływu nie przekraczają maksymalnych dopuszczalnych prędkości przepływu. Najbardziej krytyczne gradienty występowały w przypadku podwyższenia poziomu wody podczas budowy grodzi 1 i grodzi 2. Osiągnęły one wartości 0,35 i 0,34, co jest poniżej maksymalnego gradientu hydraulicznego. Obecność przecieków wody na zboczu od strony odpowietrznej stwarza jednak problem, który wymaga lokalnego zabezpieczenia z wykorzystaniem kompozytowej bariery geosyntetycznej oraz ciągłych obserwacji.

Słowa kluczowe: prędkość przepływu, pomiary instrumentów, gradient hydrauliczny

CONTENTS

Md Khorshed Alam, Arvin Farid Hydraulic conductivity tensor of anisotropic soils: the impact on seepage flow	1
Maja Sutkowska, Anna Stefańska, Magdalena Daria Vaverkova, Yasuhiro Matsui Fostering sustainable urban development: integrating school areas to support the city's green-blue infrastructure	12
Ivan Kernytskyy, Dmytro Volchenko, Yuriy Royko, Dmytro Zhuravlev, Bohdan Dolishniy, Iryna Bekish, Vasyl Rys, Ruslan Humeniuk, Yaroslav Sholudko, Oksana Berezovetska, Olga Szlachetka Complex heat exchange in brake friction pairs	32
Mikolaj Donderewicz, Kinga Rybak-Niedziółka Pre-design analyses of the mutual relationship and location of multi-family buildings using the example of the architectural and spatial concept at Długosza 22a in Warsaw	44
Parthiban Devarajan, Alicja Kozarzewska, Dhanasingh Sivalinga Vijayan, Sanjay Kumar, Arvindan Sivasuriyan, Wiktor Sitek Transformational green sustainable concepts in the field of infrastructure	56
Sanjay Kumar, Dhanasingh Sivalinga Vijayan, Parthiban Devarajan, Arvindan Sivasuriyan, Eugeniusz Koda, Wiktor Sitek, Łukasz Wodzyński Development of advanced solar panel technologies in buildings – A review	79
Paulina Filas-Zajac, Jacek Wojciech Kwiatkowski The cyclical nature of dualistic trends in urban design. Historical analysis of the creative attitudes of selected masters over the centuries	94
Volodymyr Tyvoniuk, Roman Trach, Tomasz Wierzbicki Bridge management systems: an overview and comparison	112
Anna Piętocha The BREEAM, the LEED and the DGNB certifications as an aspect of sustainable development	121
Vadim Griniov The strength of complex compressed reinforced concrete structures utilising hollow concrete blocks	134
Mateusz Miszko, Matylda Tankiewicz The influence of excavation support construction on the settlement of adjacent structures	145
Grzegorz Glinko Visualisation in architecture – opportunities and threats	157
Joanna Pietrzak Opportunities of building tall and green – an overview from a European perspective	167
Michał Kosakiewicz, Karolina Krysińska, Aneta Czachowicz, Magdalena Daria Vaverková Promoting environmental sustainability in construction: exploring implemented solutions through case studies	189
Joanna Maria Koszewska <i>Common good</i> in the urban context – insights from theoretical frameworks	210
Ivan Aftanaziv, Inga Svidrak, Orysia Strohan, Yuriy Royko, Vasyl Rys, Dmytro Bielikov, Ivan Kernytskyy Determining the coordinates of unmanned aerial vehicles	223
Yentriani Rumeta Lumbantobing, Lailia Hifziati, Rinda Kustina, Mulyadi Gunawan A comparative analysis of landfill practice between Poland and Indonesia	231
Jacek Karpiesiuk The main strength material parameters of deformable cement adhesives	246

Katarzyna Walasek, Dariusz Walasek, Magdalena Pramfelt A comparison of professional liability of architects in Poland and Sweden	257
Łukasz Wodzyński, Dorota Kula, Ewaryst Wierzbicki An analysis of the suppression of a pair of odd and even temperature fluctuation in an area occupied by a two-phase one-directional periodically layered composite	264
Karol Głażewski, Magdalena Daria Vaverková Landfill reclamation using the example of the municipal waste disposal plant in Puławy – a case study ...	274
Małgorzata Kurcjuś, Karolina Krysińska, Michał Kosakiewicz, Maurycy Naliwajko, Zofia Jabłońska, Karolina Radecka, Ewa Grzegorzewska, Michał Sieczych, Eliza Ferenc-Pupek, Anna Stefańska Integrating building information modelling (BIM) into construction: innovations, challenges, and global perspectives	287
Agnieszka Starzyk, Nuno D. Cortiços, Carlos C. Duarte, Przemysław Łacek Environmental and architectural aspects of wooden construction: a comparative analysis of selected issues of single-family housing in Poland and Portugal	304
Anna Podlasek, Anna Gmur Laboratory studies on the effects of oil pollution on soil properties	319
Ivanna Voronkova Peculiarities of functional and planning organisation of university libraries	329
Ewelina Kubacka, Piotr Ostrowski The Influence of microstructure size on temperature distribution in biperiodic composite	340
Ivan Aftanaziv, Orysia Strohan, Inga Svidrak, Nazarii Kernytskyy, Yuriy Royko, Oksana Berezovetska, Dmytro Bielikov, Marek Chalecki Increasing the durability of large-calibre cannon barrels through strengthening them by surface plastic deformation	351
Karol Zawada, Mikołaj Donderewicz, Agnieszka Gertner, Kinga Rybak-Niedziółka The impact of BIM and GIS on the efficiency of implementing construction projects	358
Marina Kravchenko, Tetiana Tkachenko, Viktor Mileikovskiy, Yuliia Trach Quantitative assessment of hydrological efficiency of rain garden design in the context of managing the volume and quality of storm effluent	369
Noor Halim, Zbigniew Lechowicz, Mirosław Lipiński Seepage analysis of the Mamak Dam, Indonesia: a case study	384

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