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ARCHITECTURAL ANALYSIS OF PHOTOVOLTAIC (PV) MODULE APPLICATIONS ON NON-FLAT ROOFS

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ABSTRACT

Due to the growing importance of renewable energy sources (RES) technology, a noticeable increase in interest in photovoltaics can be observed. Roofs most often provide the places where photovoltaic (PV) modules are installed. In many cases, ill-considered decisions concerning the selection of PV modules and their installation lead to unfavourable architectural effects. The article aims to examine the possibility of integrating PV modules installed on non-flat roofs with the broadly understood building architecture. An observational method based on case studies was applied to the study. Not only aesthetic aspects but also functional and technical aspects were considered while paying attention to energy issues. The conducted analysis indicates a good level of possibilities for integrating PV modules with architecture and these possibilities vary depending on the geometric features of the roof. Applications within full and glazed roofs are also rather distinctive.

Keywords: photovoltaics, PV modules, solar architecture, roofs, BIPV

INTRODUCTION

Placing photovoltaic (PV) modules on a building's roof generally guarantees a maximum level of exposure to the sun and a reduced risk of shadowing by the surrounding objects. With regards to climatic conditions and a latitude similar to Polish conditions, in the case of southern exposure – which is considered most advantageous – PV modules inclined at an angle of 35° to the horizontal ground generate approx. 28% more energy per year than modules placed along the vertical plane. In the case of eastern and western orientation, the difference is 44% and 43%, respectively (Roberts & Guariento, 2009).

Hence, roofs with such or similar inclinations and orientations provide a conveniently shaped surface upon which PV modules can be applied.

According to research conducted in 2017, the use of PV systems within the roof reached almost 80%, as compared to 20% within the facade (Shukla, Sudhakar & Baredar, 2017).

The application of PV modules on non-flat roofs requires a separate discussion, as significant differences can be observed in this case compared to PV applications on horizontal roofs. These applications were discussed in a separate publication (Marchwiński, 2022). First of all, the use of PV modules on non-flat roofs is characterised by a greater dependence on the exposure to the cardinal directions – differently oriented roof planes receive various amounts of insolation. As already mentioned, southern exposure is generally considered the most favourable annually; it is followed by eastern and western exposure (Chwieduk, 2011). Apart from some PV technologies and flat roof applications, northern orientation is not recommended for PV installations (Waseed, 2014).

From an architectural point of view, the exposure of the PV modules in the building's body is another significant difference. Horizontal roofs are naturally subject to weaker visual perception, which is why the rank of PV elements as a tool of aesthetic creation is potentially reduced. The flatter the roof is, the

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weaker the visual perception. Larger free space also results in less sublime forms of integrating photovoltaics with architecture – PV elements are more often installed as a monofunctional installation, which plays no other role than being an electricity generator. Unfortunately, this phenomenon also applies to non-flat roofs, mainly gable roofs, which often exert a negative impact on the architectural form of the building, especially when the use of PV modules was not originally planned. With the launch of government programmes and the resulting growing interest in photovoltaics among individual consumers, disastrous aesthetic effects are increasingly experienced.

This article aims at exploring the possibility of integrating PV modules within non-flat roofs with the broadly understood building architecture. Not only aesthetic aspects were considered, but also those related to the architectural and construction design, namely regarding utility and technical-construction aspects. Efforts were made not to lose sight of the energy issues, as these provide the primary reason for reaching for PV systems and should be considered together with the above-mentioned aspects (Lucchi, Baiani & Altamura, 2023).

MATERIAL AND METHODS

The observational method (Pieter, 1975) of a quantitative character was used in the article. The research is descriptive and based on the selected examples of buildings; it is an overview of solutions for PV applications within non-flat roofs subjected to architectural analysis. This analysis was conducted according to a general division into solid and glazed roof applications. The analysis has been supported by eight case studies – these are the non-residential buildings that have been selected to illustrate different approaches to the issue of PV integration with non-flat roofs in architecture. Roofs being tensile structures with the use of textile and foil coverings were excluded from the considerations; this case was discussed in more detail in a separate article (Milosevic & Marchwiński, 2022).

The insights resulting from the analysis were collected in a summary of the discussed PV applications, which provides the research synthesis. The synthesis made it possible to reach conclusions, the content of which provides the execution of the aim of this article.

ANALYSIS OF APPLICATIONS OF PV MODULES WITHIN NON-FLAT ROOFS

No definition of a flat and non-flat roof can be found in the legal regulations. According to the Polish PN-B-10425:1989 standard, which is commonly used to separate these concepts, the non-flat roof is a roof inclined at an angle of greater than 12° (Polski Komitet Normalizacyjny [PKN], 1989). However, for the purposes of this article, intuitive perception was applied. Non-flat roofs were treated as all roof planes whose geometry is visually perceived as non-horizontal.

Solid roofs

Photovoltaic modules applied on solid roofs come in the form of non-transparent modules. As elements added to the existing roofing (so-called building-added photovoltaics – BAPV), they are shaped as frame modules in thick-layer PV cell technology. In the case of building-integrated photovoltaics (BIPV), these modules act as cladding elements that replace these coverings (e.g., roof tiles). In the case of more sophisticated shapes (e.g., strongly bent elements), PV modules in thin-film PV cell technology may be the only possibility.

Gable roofs

The use of PV modules within traditional, existing gable roofs as BAPV, e.g., in single-family houses covered with tiles, generally brings few positive aesthetic effects. The modules applied upon the roof cover differ in both size and plastic features (colour, texture, shine), which makes them perceivable as a foreign, artificially added installation element. Replacing traditional roofing with PV modules is a difficult task, as, unlike tiles or other traditional roofing, the surface of the PV module requires ventilation from the inside. In general, solutions that do not adhere to the roof slope also look unfavourable. These, however, are less common solutions; they are only applied in such cases as when the roof slopes are unfavourably oriented.

These disadvantages are mitigated or disappear when PV modules are applied as roofing, e.g., tiles (BIPV), as well as when their application was planned before the roof was installed. This approach brings interesting and original aesthetic effects. The new tile equipped with PV cells and covered with glass with a metallic texture gives the surface a shiny, modern look while maintaining the familiar divisions. Manufacturers generally provide for appropriately prepared construction systems. This is another advantage of a system solution. The base surface is adapted to ensure the optimal operation of the modules, e.g., it provides adequate ventilation space, which positively affects the cooling of the module from the bottom and thus leads to maintaining its power generation efficiency.

In the Ho-Oh High School gymnasium building (arch. Shimomai Architectural Design) in Kagoshima (Japan), the roof slopes were covered with small rectangular PV modules as roof tiles (Fig. 1). The installation's peak power equals as much as 151 kW. The shiny roof surface, combined with the overlapping module layout analogous to the layout of traditional tiles, creates an innovative combination of tradition and modernity. As is characteristic of Japanese architecture, the roof slope has a curved profile. Its inclination angle varies from 27° to 11° to the ground. The PV modules were placed on a specially prepared steel construction frame.

The problem with this type of application lies in the aspect of aesthetic unification of all slopes, including the shaded ones, where it is irrational to apply PV modules. In such cases, the introduction of imitation elements may be required, such as glass end caps whose appearance is similar to that of the PV module.

Shed roofs

Another type of non-flat roof which provides a common base surface for PV modules is shed roofs, including the so-called saw-tooth roof. Both in newly designed and modernised buildings, these types of roofs are willingly used as a base surface for PV modules, as long as they are orientated towards the south and are not shaded. The main advantage of this solution results from the fact that the favourable inclination of the modules is obtained with no need for a structural frame. This translates into financial savings and ease of assembly. In general, the slope of the shed roofs is in line with the functional premises. The southern roof surfaces are covered with PV modules, while the northern surfaces can be glazed and thus provide diffused daylight access. Such solutions are beneficial in

Fig. 1. Photovoltaic modules integrated with the gabled roof – Ho-Oh High School gymnasium building in Kagoshima, Japan

Source: the author's elaboration on the basis of the New Energy and Industrial Technology Development Organization [NEDO] (2011).

buildings where top-down natural lighting is required or desired. At the same time, chiaroscuro contrasts, and the direct solar radiation access that can cause interior overheating are avoided. An example of such buildings is industrial halls (Szparkowski, 1999). Moreover, such solutions occur more and more frequently in such types of buildings as sports halls, art galleries, and residential or educational facilities.

The building of the Annie E. Fales Elementary School in Westborough Massachusetts, erected in 2021 (arch. HMFH Architects), has a rather unusual saw-tooth roof whose area equals 1,900 m^2. The sheds are arranged in eleven irregular rows (Fig. 2). A total of 1,350 PV modules with a total capacity of 507.75 kWp were installed on their southern slopes. The northern planes have been glazed. The layout of the sheds has been adapted to optimise solar energy gains and to illuminate the classrooms. The eleven saw-tooth rows have a total length of 19.8–57 m. On the southern side, the slope of the roofs ranges from 21° to 30°, whereas on the northern side – 54°–90°. The individual heights of each "saw-tooth", from the roof level to the top, range from 2.13 m to 3.66 m.

The cell technology used in the PV modules (manufacturer-REC) is interesting. High-efficiency PV cells (21.4%) with a power of 3.1 W each were made in the "half-cut" technology, which helps to improve the energy efficiency of the PV system. Half-cut modules are designed in such as way that the top and bottom half of each panel operate independently for maximum output. The use of light and reflective waterproofing materials on the roof is also beneficial in this case (RoofingAdmin, 2022).

Roofs with untypical geometry

The layout of PV modules on traditional roofs of existing buildings may be faced with several problems. The basic problem results from the need to arrange the modules in such a way that their surface remains unshaded throughout the year, at least in the summer, late spring, and early autumn periods when insolation is the strongest. Usually, however, despite the significant "free" roof area, it is periodically shaded by various elements existing there, such as gravitational, smoke, and exhaust chimneys, telephone exchanges, air-conditioning centres, antenna masts, superstructures, high cornices, and parapets, etc.

The construction requirements regarding the maximum loads that the flat roof can carry should also be considered. Another limitation results from the technical conditions and construction standards concerning such aspects as height relations between chimneys or air-conditioning outlets and other elements of the building's roof.

Fig. 2. Photovoltaic modules on the shed roof – Annie E. Fales Elementary School in Westborough, Massachusetts, USA

Source: ®HMFH Architects.

The search for the best location and exposure for the PV modules can lead to interesting architectural solutions. The business promotion centre office building in Duisburg (architect Norman Foster) was provided with a southern slope thanks to its body being "chopped" (Fig. 3a). The slope was used to accommodate a set of PV modules and solar thermal collectors. As a result, the building gained an unusual spatial form. These elements are not visible from the ground floor level, so there is no direct aesthetic role of these elements. However, if the shape of the building's body is considered a consequence of their application, the indirect impact is significant.

An analogous case, although completely different in its aesthetic expression, is the building of the solar cell plant in Gelsenkirchen (arch. Hohaus, Hinz & Seifert) – a manufacturer of PV modules (Fig. 3b). The office part, which is located in the front part of the building on the southern side features an original spatial shape. Its profile is curved into an arch, which creates a smooth transition from the roof part to the facade. Full fragments of the partition over its entire surface were clad with frame PV modules made of polycrystalline silicon cells. It has been shown that even thick-film technologies can be used in BIPV on curved surfaces in some cases. The modules were mounted on a trapezoidal sheet metal base. The cross-section of the sheet creates a convenient base to provide air-flow under the module for cooling, which increases the efficiency of the PV system (ATB Becker, 2006). The front of the building clad with PV modules is complemented by a greenhouse structure whose laminated glazing is also equipped with PV cells. The use of PV modules on the most exposed part of the building provides the most advantageous feature in terms of energy; open foreground, orientation to the south, and the arch, which offers a convenient inclination to the sun's rays, and ensures the effective operation of the PV system. This solution was also dictated by aesthetic considerations; it aimed to create a sort of advertisement for the company's products.

Glazed roofs

Apart from being located on traditional roofs, PV modules are increasingly used within glazed roofs. This is another step in the development of PV technology in construction and architecture.

Photovoltaic modules can replace traditional glazing panels. They create laminated glazing, in which the inner layer is made of PV cells, as in the case of modules to be used within facades, except that roof modules usually require different technological solutions, e.g.,

a b

Fig. 3. Photovoltaic modules on curved roofs: a – business promotion centre office building in Duisburg, Germany; b – solar cell plant in Gelsenkirchen, Germany

Source: the author's collection.

glazing with increased resistance to mechanical loads. They are also available in the form of shading systems, the so-called shadow-voltaic systems.

Coverings of greenhouse structures

One of the most interesting implementations of a glazed roof where PV technology is used is the ECN-42 office and laboratory building in Petten (the Netherlands), designed by BEAR Architecten, a well-known Dutch design office.

Photovoltaic modules from "BP Solar", whose total area equals approx. 400 m^2, with a power of 42 kWp, were used in the upper part of the greenhouse, which forms a kind of winter garden in the building (Fig. 4).

The greenhouse was shaped as a dynamic volume with an arched profile. This curvature not only enhances the architectural expression but also helps to obtain a convenient inclination angle for the PV modules. The glazing has a favourable south orientation. Each PV module contains 32 offset monocrystalline silicon PV cells. The layout of the cells causes light to pass between the gaps. The separation is from 1–2 cm, depending on the module, whereas the light transmission amounts to 30%. In this way, the modules play the role of shading elements; they filter sunlight and introduce it into the interior in a diffused form. This prevents the effect of excessive luminance and overheating of the greenhouse in the summer. In winter, when the sun is low above the horizon, the sun's rays can penetrate directly into the interior through fully glazed panels located in the lower part of the partition. Passive solar gains are possible.

Being a temporarily used space, the greenhouse is not heated traditionally. It acts as a thermal buffer or solar heat collector.

The greenhouse has a wooden structure, which is yet another manifestation of holistic pro-ecological thought in shaping the building's architecture. Material from renewable sources with low demand for so-called embodied energy, that is, the energy needed for its manufacturing, is used. The structure comprises bent beams made of laminated timber. The repeating structural element called the main beam is composed of two individual wooden beams connected by steel profiles. Aluminium profiles are attached to the upper outer surface of the beam, which constitutes the structure for both the glass panels and the roof of the PV modules. Particular effort was required to obtain the curvature of the module surface in accordance with the geometry of the beams. Each element was cut and bent every 120 mm to create an impression of a smoothly curved plane. The modules are 575 × 1,175 mm. Thus, the modular division has been preserved, which introduces harmony and order in the facade (BEAR Architecten, 2011).

Coverings for atriums – atrium skylights

In the office and laboratory building of the Fraunhofer Institute in Freiburg, Germany, designed by Dissing+Weitling, a glass roof with PV technology

Fig. 4. Glazed BIPV as a covering for a winter garden in the ECN-42 office building in Petten, the Netherlands

Source: BEAR Architecten (2011).

covers the inner atrium (Fig. 5a). The roof geometry, which is characterised by a "saw-tooth" cross-section, is interesting. Semi-transparent PV modules that form the roof are arranged in series and inclined at a certain angle. The vertical surfaces, which are created as a result of the modules' inclination, have been filled with transparent glazing.

Despite the introduction of vertical glazing and spreading the PV cells apart within the modules, the intimate atrium is poorly lit, which may make its space perceived as cramped and gloomy. On the other hand, the roof solution introduces an artistic "play" of light and shadow. Since the atrium serves as a communication space and does not require high illumination standards, the level of natural lighting can be considered sufficient in the functional context.

Limitations regarding the use of PV modules in the glass coverings of central atriums (surrounded by walls on four sides) become apparent when the covering is arranged in the form of a roof, dome, barrel vault, or other spatial forms that introduce a division into planes with different orientations regarding the cardinal directions. As the PV modules should only be installed on the sunlit parts of the roof, it is not rational to distribute them fully or evenly across the entire structure. In the building of the Technical University of Munich, the glass covering of the central atrium has the form of a barrel vault (Fig. 5b). Photovoltaic modules occupy only the lower part of the southern plane of the cradle. The remaining surface is filled with glass panels. This solution allows for significant use of daylight but fails to protect well against strong summer radiation when the sun is high in the sky. In winter, the semi-transparent modules serve as a barrier to sun rays that fall at a lower angle, which is desirable during this period. It should also be pointed out that the use of modules in this type of cover is limited in terms of area, thus, in the total power of the PV installation. In the Munich building, the total peak power is less than 19 kW (New Energy and Industrial Technology Development Organization [NEDO], 2011).

A different approach to the use of PV modules within glazed roofs is presented in the building of the European Headquarters of Digital Equipment Corporation in Geneva (arch. Lecouturier & Caduff). The pyramid-shaped glass roof that covers the inner atrium is equipped with densely spaced PV modules in the form of horizontal shading lamel-

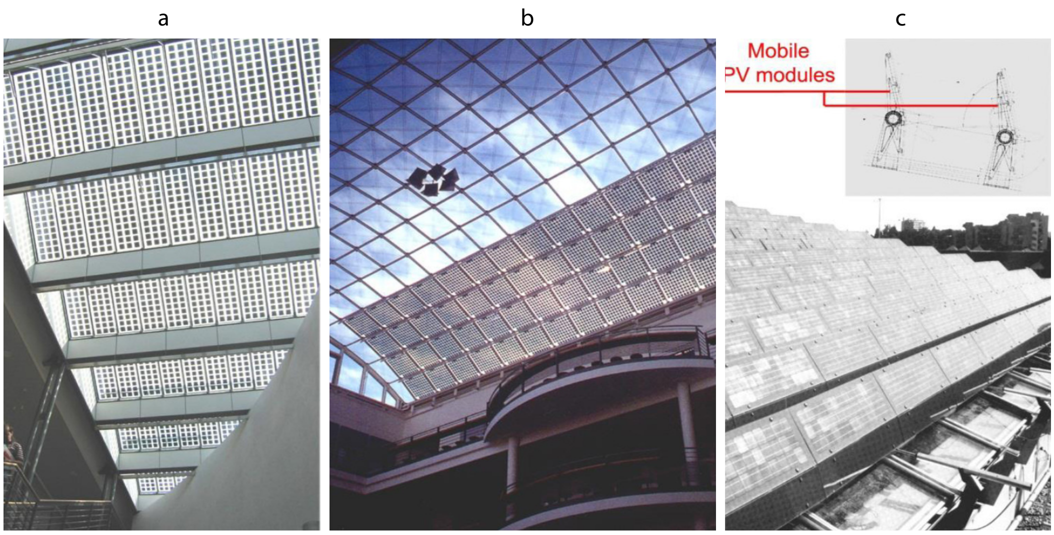

Fig. 5. Glazed BIPV as a covering for atriums in: the office and laboratory building of the Fraunhofer Institute in Freiburg, Germany (a); Technical University building in Munich, Germany (b); building of the European Headquarters of Digital Equipment Corporation in Geneva, Switzerland (c)

Source: [a]the author's collection; [b]NEDO (2011); [c]Humm & Toggweiler (1993).

las (Fig. 5c). These modules were attached to the glazing structure from the outside. The elements cover three surfaces of the glass roof, except for the northern part, where traditional external slats have been introduced. The PV modules were equipped with follow-up devices. They can change their position by adjusting the angle of inclination to the direction of the sun's rays. This solution is of great importance in terms of obtaining solar heat in winter and protection against overheating of the interior in the summer. It also helps to optimise the use of natural light. Finally, the variability of the position of the modules increases the aesthetic value of the atrial space (Humm & Toggweiler, 1993).

RESULTS

The following section includes a summary of the PV module applications within solid and glazed roofs. The list concerns the most crucial aspects from the architectural point of view, namely aesthetic, functional, and technical (Table 1).

Table 1. Comparison of the PV modules application within solid and glazed roofs

Aspect	PVs – solid roofs	PVs – glazed roofs
Aesthetic	Relatively strong direct impact on the building's architecture when used on sloped roofs (impact through colour, texture, roofing divisions); the influence increases with the growth of slope deviation from the horizontal axis. Applications of BAPV generally do not offer beneficial aesthetic effects (visual distinctiveness); it may require the imitation of modules in less sunny areas in order to obtain a homogeneous aesthetic expression of the entire roof. In the case of newly designed buildings, an indirect aesthetic impact may be achieved, i.e., the impact of energy considerations related to maximising the operation of PV modules on the roof geometry. In the case of gable roofs, the direct influence on the building's aesthetic function is limited, due to the relatively poor exposure in the entire building's body. In the case of arched profiles, the effect is potentially much stronger; the boundary between the roof and the facade is blurred, which makes it possible to use PV modules in creating expressive architectural forms.	Elements of PV provide a component of external glass partitions or solar shading systems. For this reason, they generally result in favourable effects in terms of architectural integration. From the outside, shadow-voltaic systems on arched roofs, if the boundary between the roof and the facade is blurred, potentially exert the strongest impact. However, what should be considered is the direct aesthetic impact on the internal space when the PV elements are visible from the inside. It concerns the plastic and compositional features of the glass roof (texture, colour divisions). Indirectly, the impact on internal space is exerted through the impact on internal lighting (change of light intensity and even a colourful chiaroscuro effect can be an element of aesthetic creation). Indirect impact, as in solid roofs, may consist in adjusting the geometry of glass roofs to the energy needs of PV modules, i.e., creating the most favourable solar exposure (e.g., glass roofs).
Functional	Limited impact. Indirectly, it is related to the restrictions on the introduction of roof elements that could shade the modules, as well as elements that limit the PV modules' total area (e.g., numerous and large roof windows). South-oriented shed roofs create favourable conditions to meet the aspirations for favourable natural lighting of interiors while meeting the energy conditions related to the requirements of the PV modules' operation.	Potentially significant impact on shaping the visual and thermal environment of the space under the PV glass roof. The possibility to use PV modules as shading elements (solar glazing and shadow-voltaic systems). Semi-transparent modules with distanced PV cells may be inadequate in spaces that require diffused natural light, devoid of chiaroscuro contrasts. For this reason, they are more suitable for covering public spaces (e.g., courtyards, and entrance halls). Another problem may be related to the need to reconcile the efforts to create high-power PV installations with the premises regarding effective natural lighting.
Technical	PV modules require a base surface that provides effective cooling from underneath (e.g., a trapezoidal sheet). System solutions tailored to a specific manufacturer are recommended. It may also be important to adjust the roof covering in terms of reflecting light (albedo); bright, glossy materials can increase the influx of solar radiation (especially in shed roofs).	In the case of glazing-integrated PV elements, the impact is limited – these elements use support systems for glass roofs. The profiles of the glass systems should make it possible to conceal the wiring and connection sockets. Shadow-voltaic systems require a base surface analogous to traditional external solar protection systems.
	Indirect impact consists in adapting the structure to the roof profile, which results from energy conditions related to the PV elements' inclination.	

Source: own elaboration.

DISCUSSION AND CONCLUSIONS

The conducted analysis indicates a good deal of possibilities to integrate PV modules used on non-flat roofs with the broadly understood building architecture. These possibilities vary depending on the type of roof. The differences concern all three aspects: aesthetic, functional, and technical. It should also be noted that a difference in the use of PV technology within solid and glazed roofs is likely.

Further detailed research is required. The glazing application of BIPV in the energy context seems especially interesting. The search for balance between energy gains from photovoltaics and the use of natural light is a crucial issue. Other issues that require more attention are: the potential of BIPV in shaping flat roofs, regarded as the "fifth facade", and the influence of glazed PV roof elements applications on the thermal and visual internal environment of the building.

The following general conclusions can be drawn from the analyses:

- Photovoltaic technology should be taken into account during the design phase. This mainly applies to its applications within solid roofs. Then, the possibilities for successful integration of PV modules with architecture increase, both in the aesthetic and technical context. These modules are used within glazed roofs and generally serve as elements that are strongly integrated into the building's architecture, as they are a building component rather than a separate installation.
- In addition to the direct impact of PV modules on the building's architecture, activities involving shaping the building body under the influence of their application should be considered an interesting manifestation of the integration of PV technology with architecture.
- The problem of the lack of architectural visibility of roof-based PV modules applies only in some cases (e.g., roofs with a small slope and the majority of shed roofs).
- The impact of PV modules on the aesthetic aspect is more related to the building's body in the case of applications within solid roofs and the internal space in the case of applications within glazed roofs.
- Compared to solid roofs, the use of PV modules within glass roofs offers greater possibilities to take advantage of these elements while shaping the thermal and visual environment. These modules should be seen as part of the strategy of coupling with solar architecture, also in order to increase their role in the building.
- The use of PV modules within roofs should form a consensus between the desire to maximise energy gains and the utility requirements in terms of ensuring natural lighting of interiors, also in terms of energy benefits.

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ANALIZA ARCHITEKTONICZNA APLIKACJI MODUŁÓW FOTOWOLTAICZNYCH (PV) NA DACHACH NIEPŁASKICH

STRESZCZENIE

Za sprawą rosnącego znaczenia technologii z wykorzystaniem odnawialnych źródeł energii (OZE) obserwuje się wzrost zainteresowania fotowoltaiką. Dachy budynków często stanowią miejsce montażu modułów fotowoltaicznych (PV). Nieprzemyślane decyzje o doborze i sposobie zamontowania modułów PV niejednokrotnie prowadzą do niekorzystnych efektów architektonicznych. Artykuł ma na celu zbadanie możliwości integracji modułów PV w obrębie dachów niepłaskich z szeroko rozumianą architekturą budynku. Wykorzystano metodę obserwacyjną z zastosowaniem analizy przypadków. Pod uwagę wzięto nie tylko aspekty estetyczne, ale także funkcjonalne i techniczne, rozważono również aspekty energetycznych. Przeprowadzona analiza wskazuje na duże możliwości integracji modułów PV z architekturą. Możliwości te są zróżnicowane w zależności od cech geometrycznych dachu. Odrębnością cechują się również rozwiązania techniczne tego typu stosowane na dachów pełnych i przeszklonych.

Słowa kluczowe: fotowoltaika, moduły fotowoltaiczne PV, architektura słoneczna, dachy, BIPV

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SIZING OPTIMISATION OF STEEL TRUSS BASED ON ALGORITHMS

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ABSTRACT

Computational methods enable mathematical discretisation in structural design. Thus, thanks to the algorithmic design, the obtained results matrix presents various structurally efficient load-bearing elements. The main aim of this paper is to address the topic of material optimisation in truss bar structures with different approaches. The paper analyses and compares steel truss optimisation based on two software optimisation algorithms (MS Excel and Ansys Mechanical) using gradient and sub-problem methods. The key findings present how effective each method is in structural optimisation and concludes the present study with a roadmap to efficient structural designing of the load-bearing truss elements.

Keywords: structural optimisation, computer methods in structural engineering, truss optimisation, finite elements method

INTRODUCTION

Computer programs make it possible to consciously apply selected methods that, by understanding the working principles of engineering structures, give engineers the expected results and enable creative professional activity. A structure is a real object with inherent errors in the components' manufacturing and assembling process and has unavoidable imperfections. The basic model of the structure is created using theoretical assumptions and simplifications that result from theories describing physical phenomena so that the object's basic scheme of operation can be adopted, for example: frames, plates, and shells. The computer model is formed by approximate discretisation, which is necessary since computers operate with numbers, not functions (Logg, 2007). The essence of modelling is a simplification in which we analyse the dominant effects and omit the less important ones. Without losing the accuracy of the solution, it is usually possible to reduce the spatial structure and complex stress state to a one- or two-dimensional system. Subsequent models are generally more far-reaching simplifications created for specific theories or methods. It is worth noting that even the simplest structural systems would be impossible to solve without simplification.

Computer methods include the transition method from a continuum to a discrete system and the solution algorithm. Their common feature is the reduction of differential equations (e.g., equilibrium equations) to corresponding systems of algebraic equations. On the other hand, the main differences in computer methods concern the manner of discretisation and approximation of the function sought (Logg, 2007).

Even before the advent of computers, approximate methods for solving differential equations were developed and are still used today. They use mathematical discretisation because the coefficients have

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no direct counterparts in physical/mechanical quantities. Examples include the development of functions into the Taylor series, Fourier series, Ritz and Galerkin approximation methods and the finite difference method (approximation of derivatives by differential quotients). When creating the finite element analysis (FEA) model, discretisation involves dividing an area into elements that share nodes and contain mutual neighbourhood information. On the continuum, one looks for a function $f(x, y)$ that satisfies certain differential equations. In the discrete model, on the other hand, the search is for a set (vector) of numbers $f(x_i, y_i)$ at selected points on the continuum, which satisfies a mostly linear system of equations.

Classical methods of structural analysis, such as the force, displacement, or cross methods, have also played a significant role in developing computational methods. They use physical discretisation (unknown degrees of freedom of the system correspond to actual physical quantities, such as generalised displacements of nodes). The most widely used and comprehensive method in computerised structural analysis today is the finite element method (FEM). Alternatives to FEM include the boundary element method, meshless/meshfree methods and mathematical discretisation methods (Kirby, Logg, Scott & Terrel, 2006).

STATE OF THE ART

Environmental pollution

Architectural objectives include designing features such as usability, aesthetics and environmental processes (Kurcjusz, Stefańska, Dixit & Starzyk, 2022). Steel manufacturing industries are responsible for consuming large amounts of energy and fossil fuels; they are also a significant part of greenhouse gas emissions (Burchart-Korol, 2013). It is considered that around half of the greenhouse gas emissions are related to structural building materials (Webster et al., 2012). In recent years, there have been attempts to use alternative sustainable materials that would not negatively impact the environment (Vijayan et al., 2022).

According to studies, the construction sector strongly impacts environmental changes. In the European Union, construction is responsible for about 50% of natural resource consumption, in addition to the total energy consumption of 42%, greenhouse gas emissions of 35%, and waste flows of 32% (Pomponi & Moncaster, 2016). A significant portion of global greenhouse gas emissions comes from the production and processing of building materials. Despite this, a lot of material is wasted in construction due to over-dimensioned load-bearing structures. While numerical optimisation tools have the potential to decrease the usage of structural materials, their use in daily design practice is hindered by the absence of tailored algorithms (Dillen, Lombaert & Schevenels, 2021). By-products of construction activities pollute the environment – it is worth noting the energy consumed and carbon dioxide emissions consumed when transporting heavy and bulky construction components (Łacek & Starzyk, 2022).

Truss optimisation

Minimising the use of materials is possible through the efficient use of natural resources, which is the responsibility of today's construction sector (Dixit & Stefańska, 2022). The general role of optimisation is to find the function's minimum or maximum with respect to the restrictions. Shape, size and topology structural optimisation can be distinguished (Stolpe, 2016). Additionally, integrated optimisation consists of previously mentioned processes (Liu & Xia, 2022). The search for effects conditioned by the rationalisation of technical solutions is a challenge in determining the optimal form, especially in applying algorithmic design tools (Stefańska & Rokicki, 2022).

Structural size optimisations of truss elements aim to minimise the structure's total weight where the structural elements' cross-sectional area is a dimensional parameter – the design variable (Renkavieski & Parpinelli, 2021). Constraints – maximum stresses or deflections – must be considered when optimising the structure's weight (Kaveh & Zaerreza, 2020; Stefańska et al., 2022). Optimisation can allow reducing the use of materials, thereby lowering construction costs (Renkavieski & Parpinelli, 2021).

With numerical optimisation tools, automating tedious parts of the design process can restore the balance between rational design and material efficiency (Dillen, Lombaert & Schevenels, 2021). Structural optimisation is essential to designing a lightweight and efficient bar system that can safely carry loads (Liu & Xia, 2022). Truss optimisation is an engineering problem that can be approached in many different ways (Table 1). Due to its peculiarity, nonlinearity and multidimensional search space, a metaheuristic algorithm can be used (Renkavieski & Parpinelli, 2021). We can distinguish between deterministic and stochastic approaches in finding the best solution to a problem (Wang et al., 2013).

Table 1. The classification of optimisation tasks

Static optimisation	Dynamic optimisation
without restrictions	with restrictions
linear programming task	nonlinear programming task
smooth	non-smooth
continual	integer
deterministic	stochastic
with a single target function	multi-criteria

Source: the authors' compilation.

Gradient-based optimisation

Gradient-based methods can be used to solve continuous optimisation problems as it requires the objective and constraint functions to be differentiable (Haftka & Gürdal, 2012). To enhance the efficiency of optimisation algorithms, such methods utilise sensitivities or gradients of objective and constraint functions for optimal performance. However, the applicability of gradient-based techniques is contingent on the differentiability of objective and constraint functions, thus rendering them capable of handling solely continuous design variables like shape variables (Dillen, Lombaert & Schevenels, 2021).

Sub-problem method

In this method, a modified objective function is constructed at the outset, which contains information about the objective function's value and the penalties for exceeding the constraints. Then, from a randomly selected set of admissible points, this function is interpolated with a polynomial of an appropriate degree and its minimum is determined, which is an algebraically simple task. This process is repeated in subsequent iterations for a narrowed search area around the best solution found in the previous iteration. The method is, therefore, relatively simple, as it does not require the calculation of gradients of the objective and constraint functions, which can be expensive when estimated numerically. Thus, despite its simplicity, it performs well in many optimisation tasks.

MATERIALS

Research methodology

The case study analyses the steel truss structures with a sizing optimisation approach of the selected bars for the truss. The objective is to make the structure as light as possible when the boundary conditions for deflections and stresses are met, so optimising the cross-sections of the truss bars reduces the steel required for the truss. Finding the smallest possible volume assumes the same steel class in all bars. The decision variables will be the cross-sectional areas in the truss bars, which will be divided into four groups – top chord bars, bottom chord bars, vertical bars, and diagonal bars.

The objective function is linear – it is the sum of rod volumes. The minimum of this function is sought, where the decision variables are the areas of the bar groups (Eq. 1).

$$\min V(A) = \sum_{i=1}^{N} A_i \cdot L_i, \quad (1)$$

where:
V – volume of the structure,
A_i – cross-section area of the given bar,
L_i – length of the given bar.

Decision variables must be bounded by a minimum value (Eq. 2).

$$A_i \geq A_0, \quad (2)$$

where:
A_i – cross-section area of the given bar,
A_0 – minimum constraint cross-section area of the bar.

Stress conditions must be met – they must fit within certain limits. The stresses are inversely proportional to the decision variable – the cross-sectional area of each group of bars. Therefore, the constraints are no longer linearly dependent.

$$\sigma_i \leq |\sigma_0|, \tag{3}$$

where:
σ_i – stresses in the given bar,
σ_0 – maximum stresses that are allowed in the bar.

$$\sigma_i = \frac{N_i}{A_i}, \tag{4}$$

where:
σ_i – stresses in the given bar,
N_i – forces acting on the cross-section area,
A_i – cross-section area.

Displacements were calculated from the Maxwell–Mohr formula (Eq. 5).

$$w = \int_V \frac{\sigma^0 \cdot \sigma^1}{E} \mathrm{d}V = \sum_{i=1}^{N} \frac{N_i^0 \cdot \bar{N}_i^1 \cdot L_i}{E \cdot A_i} \leq w_0, \tag{5}$$

where:
w – deflection,
V – volume of the structure,
σ^0 – stress,
σ^1 – stress due to unit load,
E – Young modulus,
N_i^0 – internal force,
$\bar{N}_i^1$ – internal force due to unit load,
L_i – length of the given bar,
A_i – cross-section area,
w_0 – maximum constraint deflection.

The maximum deflection for a lattice girder supported like a cantilever was limited (Eq. 6)

$$w_0 = \frac{L}{250} = \frac{500\,\text{cm}}{250} = 2\,\text{cm}. \tag{6}$$

The constraints will be the area of each bar (A_0) greater than or equal to 1 cm^2. The compressive and tensile stresses (σ_0) will not exceed 21.5 kN·cm^{-2} – the task assumes the same value for compressive and tensile stresses without considering buckling. The deflection (w_0) will not exceed 2 cm. Young modulus (E) is equal to 20,500 kN·cm^{-2}. In addition, the node between bars 3–8 will be loaded with a force (P) of 100 kN.

Truss geometry

The study's subject is a truss (Fig. 1) supported by two supports. It consists of 13 bars and is loaded by a single force concentrated at the node connecting bars 3–8. The truss presented in Figure 1 is statically undetermined twice (because of two additional bars). The preconceived bar cross-sections are shown in Table 2.

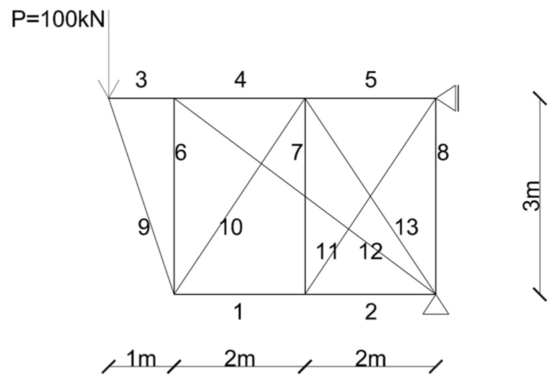


Fig. 1. Truss scheme

Source: the authors' compilation.

Table 2. Truss bars characteristics

Bars	Steel	Cross-section	Area [cm^2]
1–5	S235	RK 50 × 50 × 5	8.73
6–13	S235	RK 30 × 30 × 3	3.14

Source: the authors' compilation.

The force method

In the first step, the stresses occurring in the truss were calculated using the force method (Fig. 2) and two computer programs: MS Excel and Ansys Mechanical.

The basic layout is shown in Figure 3. Tables 3–5 show the load states from the unit forces, P forces and reactions in the supports, and the calculated forces in the bars.

Truss stresses, maximum deflection and bar volume were calculated using MS Excel. The geometry was also entered into Ansys Mechanical, and the results were obtained, which fully agree, as shown in Table 6. Stress limits were exceeded for bars S9 and S10.

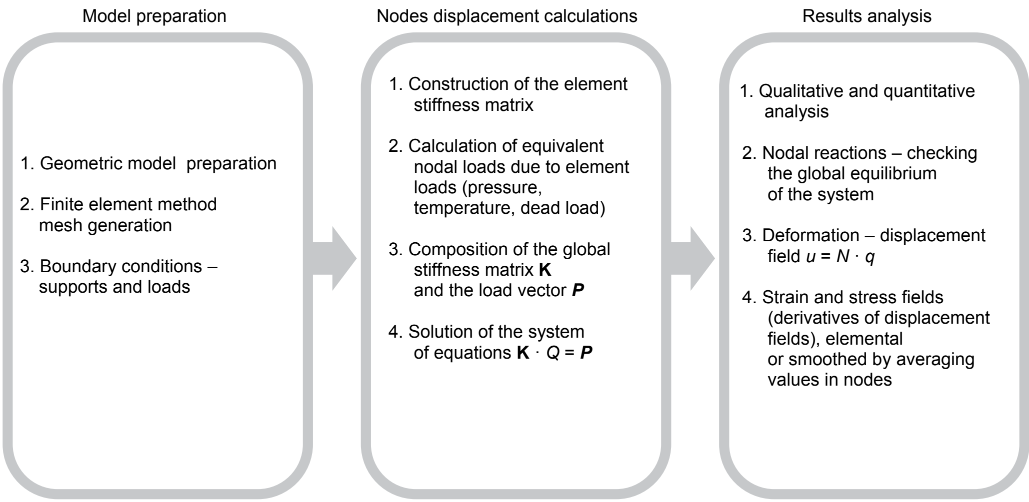


Fig. 2. General finite elements method algorithm

Source: the authors' compilation.

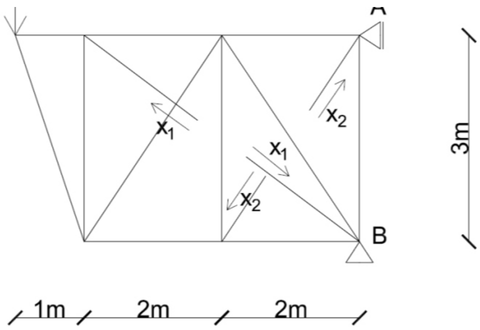
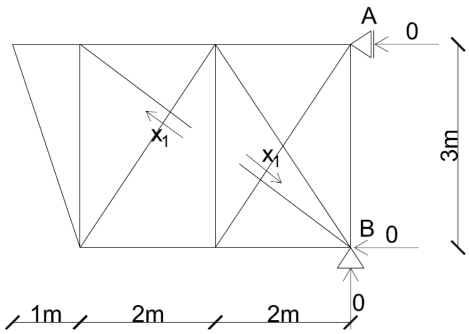
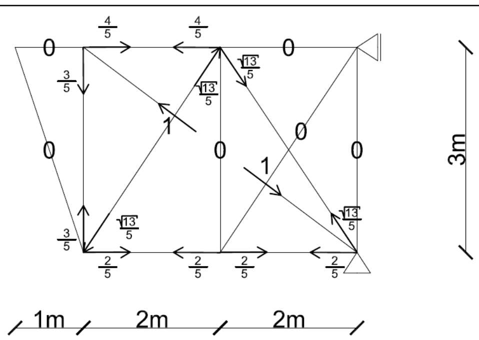


Fig. 3. Analysed truss layout

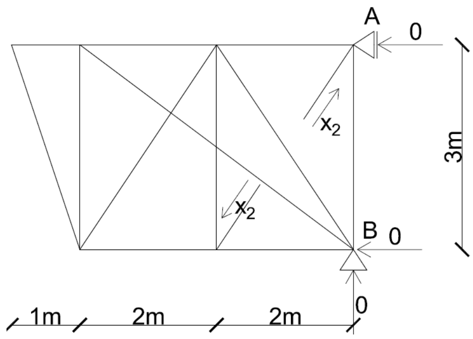
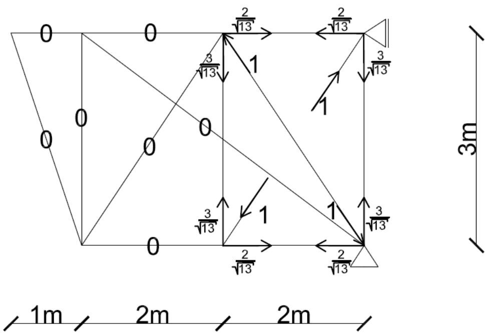
Source: the authors' compilation.

Table 3. Forces in bars for unit load $x_1 = 1$

Description	Scheme
Condition from unit load $x_1 = 1$ and reactions in supports	
Forces in the bars	

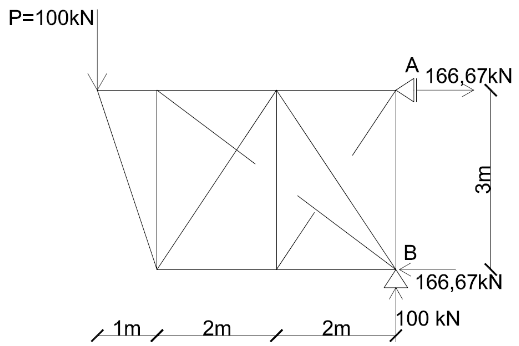
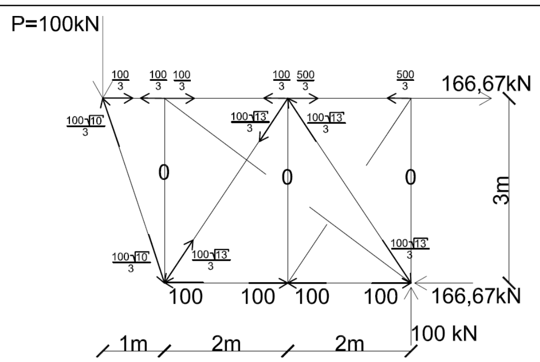
Source: the authors' compilation.

Table 4. Forces in bars for unit load $x_2 = 1$

Description	Scheme
Condition from unit load $x_2 = 1$ and reactions in supports	
Forces in the bars	

Source: the authors' compilation.

Table 5. Forces in bars for load $P = 100$ kN

Description	Scheme
Condition from load $P = 100$ kN and reactions in supports	
Forces in the bars	

Source: the authors' compilation.

Table 6. Results of a truss solved by the force method in MS Excel and Ansys Mechanical

Parameter	Unit	Ansys Mechanical	MS Excel
Bottom bars area	cm^2	8.73	8.73
Top bars area	cm^2	8.73	8.73
Diagonal bars area	cm^2	3.14	3.14
Vertical bars area	cm^2	3.14	3.14
Maximum area	cm^2	8.73	8.73
S1	$kN \cdot cm^{-2}$	–8.85515507	–8.85515507
S2	$kN \cdot cm^{-2}$	–10.5850944	–10.58509437
S3	$kN \cdot cm^{-2}$	3.81825124	3.81825124
S4	$kN \cdot cm^{-2}$	9.01744855	9.01744855
S5	$kN \cdot cm^{-2}$	17.3613169	17.36131690
S6	$kN \cdot cm^{-2}$	10.8413199	10.84131987
S7	$kN \cdot cm^{-2}$	–7.21450803	–7.21450803
S8	$kN \cdot cm^{-2}$	–7.21450803	–7.21450803
S9	$kN \cdot cm^{-2}$	–33.5698265	–33.56982654
S10	$kN \cdot cm^{-2}$	25.24584635	25.24584635
S11	$kN \cdot cm^{-2}$	8.67075954	8.67075954
S12	$kN \cdot cm^{-2}$	–18.0688665	–18.06886646
S13	$kN \cdot cm^{-2}$	–16.5750868	–16.57508680
Maximum deflection	cm	1.93736294	1.93736294
Volume	cm^3	16 642.3845	16 642.3845

Source: the authors' compilation.

Optimisation in Ansys Mechanical – the gradient method

Data were entered into the program – optimisation constraints and decision variables were defined. The program then considered the maximum allowable cross-sectional area of 100 cm^2. The decision variables will change values if the changes are greater than 0.01 cm^2. For stresses, the program will stop changing them if the changes are less than 0.01 $kN \cdot cm^{-2}$, for deflection – 0.001 cm and for volume – 0.1 cm^3.

The optimisation process to the minimum value of the function was limited to 100 steps. No value was introduced to determine how much the decision values should change at the beginning of the optimisation; the program changed them by about 5%. The program counts the derivative of the objective function for each decision variable, selects the best solution out of four, and then takes a step in that direction. The smallest value of the volume of the structure was obtained in the 28th step.

Optimisation in Ansys Mechanical – the sub-problem method

Data were entered into the program as in the gradient method. Decision variables were changed as long as no better result was obtained after 30 trials. The smallest value for the volume of the structure was obtained in the 68th step.

Optimisation in MS Excel

The bars were separated into four groups – bottom, top, diagonal, and vertical. The area fields of these bars are decision variables. The cross-sections were optimised using the solver add-on, which considered the minimum of the objective function for the truss volume. Constraints on the minimum cross-section A0, the stress limits and the maximum allowable deflection value were considered.

RESULTS

The results from MS Excel and Ansys Mechanical differ by relatively minimal values, as shown in Table 7. MS Excel performed better optimisation (lower steel volume by 0.19%), but Ansys Mechanical calculated 0.18% lower deflection.

Table 7. Truss optimisation results were obtained with Ansys Mechanical (the gradient and sub-problem method) and in MS Excel

Parameter	Unit	Ansys Mechanical		MS Excel with Solver
		Gradient method	Sub-problem method	
Bottom bars area	cm^2	4.2197	4.0065	4.000977
Top bars area	cm^2	7.5473	7.4003	7.386617
Diagonal bars area	cm^2	1.5951	1.5283	1.52326
Vertical bars area	cm^2	4.9169	4.9117	4.902756

Table 7 (cont.)

Parameter	Unit	Ansys Mechanical		MS Excel with Solver
		Gradient method	Sub--problem method	
Maximum area	cm^2	7.5473	7.4003	7.386617
S1	$kN \cdot cm^{-2}$	–18.521	–19.508	–19.53687897
S2	$kN \cdot cm^{-2}$	–20.454	–21.469	–21.49999958
S3	$kN \cdot cm^{-2}$	4.4166	4.5043	4.51266571
S4	$kN \cdot cm^{-2}$	10.206	10.408	10.42427342
S5	$kN \cdot cm^{-2}$	21.002	21.460	21.49999999
S6	$kN \cdot cm^{-2}$	20.545	21.439	21.49999990
S7	$kN \cdot cm^{-2}$	–7.6702	–7.7133	–7.73446598
S8	$kN \cdot cm^{-2}$	–7.6702	–7.7133	–7.73446598
S9	$kN \cdot cm^{-2}$	–21.438	–21.461	–21.50000000
S10	$kN \cdot cm^{-2}$	16.433	16.452	16.48549022
S11	$kN \cdot cm^{-2}$	2.9906	2.8844	2.88811488
S12	$kN \cdot cm^{-2}$	–11.109	–11.1188	–11.13322320
S13	$kN \cdot cm^{-2}$	–13.442	–13.567	–13.59737534
Maximum deflection	cm	1.7422	1.7734	1.77668250
Volume	cm^3	1 6229	16 000	15 969.5404

Source: the authors' compilation.

For the analysed truss, the sub-problem method proved more effective than the gradient method. The result obtained has enough accuracy to compare the results with those of MS Excel – the volume differs by 0.19%. MS Excel was better at optimisation, as it achieved a lower volume of steel. In contrast, the lower deflection was achieved by Ansys Mechanical (by 0.18%). Stress proved to be the decisive optimisation parameter in this case. The optimisation saved about 4% of the steel volume.

DISCUSSION AND CONCLUSIONS

The method used influences the result of the optimisation. The presented approach helps to understand the structure's operation better and provides higher efficiency. Very similar results were obtained, and each optimised the final result. Effective structural optimisation reduces the cost of a construction project due to less material used. It also translates into lower emissions of pollutants into the atmosphere.

There are many opportunities for further research on the topic, as the issue of optimisation is very complex. Another analysed issue could occur with a different division of bars into groups – instead of dividing the bars into four different groups, they could all be treated individually. They could also be divided in other ways, for example, considering the stresses that occur in them.

The studies are helpful for designers, structural engineers, architects and anyone involved in optimisation in the construction industry. Both practitioners and researchers can benefit from them.

Authors' contributions

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

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

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OPTYMALIZACJA WIELKOŚCIOWA KRATOWNICY STALOWEJ WEDŁUG ALGORYTMÓW

STRESZCZENIE

Metody obliczeniowe umożliwiają dyskretyzację matematyczną w projektowaniu konstrukcji. W ten sposób uzyskana macierz wyników, dzięki projektowaniu algorytmicznemu, prezentuje różne efektywne konstrukcyjnie elementy nośne. Głównym celem artykułu jest podjęcie tematu optymalizacji materiałowej w kratownicowych konstrukcjach prętowych przy zastosowaniu różnych podejść. W artykule przeanalizowano i porównano optymalizację kratownicy stalowej z zastosowaniem dwóch programowych algorytmów optymalizacyjnych (MS Excel i Ansys Mechanical) według metod gradientowych i programowania dynamicznego (rozwiązań podproblemów). Kluczowe wnioski przedstawiają skuteczność każdej z metod w optymalizacji strukturalnej i kończą niniejsze opracowanie instrukcją do efektywnego projektowania konstrukcyjnego elementów kratownicy nośnej.

Słowa kluczowe: optymalizacja konstrukcji, metody komputerowe w inżynierii lądowej, optymalizacja kratownicy, metoda elementów skończonych

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VIBRATION MEASUREMENT IN THE DEGRADATION STUDY OF BUILDING CONSTRUCTION MATERIALS

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ABSTRACT

Brick objects are subject to large dynamic loads clearly reflected by generated vibration processes. The vibrations may affect the state of serviceability of structures by lowering the comfort of persons working there, as well as possibly reaching a level hazardous to the safety of the structures. The effect of vibrations on the structure is mainly manifested by additional stresses in a given cross-section, which are summed up with those resulting from static loads. The dynamic loads may cause damaging effects in buildings of various structural types or even lead to their destruction. The article describes a series of original analyses of the process of destruction of selected masonry objects using the experimental modal analysis. The research was conducted to improve the quality assessment of building structures in terms of the technical condition of masonry structures and meeting safety standards.

Keywords: modal analysis, natural vibration frequency, stabilisation diagram, structural vibrations

INTRODUCTION

Modern building constructions and the production of low-noise machines and devices are associated with a high level of precision in their manufacture and the appropriate selection of materials, which greatly affect their quality, reliability and durability (Stępniewski, Uhl & Staszewski, 2013).

When studying real systems (structures, buildings, machines, equipment), the main problem is determining the energy stored, dissipated and transmitted by certain system elements. Knowledge of dimensions can be used to assess material costs, fatigue, diagnostic checks and noise level predictions, and also aids in the design of system components – e.g., vibration isolation (Allemang & Phillips, 2004).

The development of measurement methods, especially energy measurement methods, has greatly expanded the possibilities for studying sound radiation from buildings and made it possible to calculate the sound power radiated into the far field based on near-field measurements. Quantitative and qualitative research methods for the propagation of vibro-acoustic energy in spaces with complex boundary regions have been developed. It is related to the quantitative assessment of the vibro-acoustic energy stored in structural elements and the energy radiated from the elements and transmitted in different ways (Cempel, 1994).

Modern architectural structural dynamics uses various research tools in the field of state determination, such as the boundary element method, the finite element method and modal analysis methods, to better understand the behaviour of complex structures through modelling and investigation of state changes, guide their optimisation during the design process and assess their current – often dangerous – conditions (Cempel, 2003).

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Considering the need to improve research methods dealing with the quality of brick structures in order to assess the condition and safety factor of brick structures (see Polish standard PN-B-03002 by Polski Komitet Normalizacyjny [PKN], 2007), in this work, the author attempted to develop research methods by using the experimental modal analysis method to evaluate the failure quality of selected building structures.

There is a need for improved methods for studying the dynamic behaviour of structures, especially those subjected to large dynamic loads. New materials and technical methods are introduced into construction projects, as well as novel constructive solutions, which allow for increased productivity and product quality, but are accompanied by huge, often dangerous, dynamic loads. The problem is receiving more and more attention (Stępniewski et al., 2013).

Vibration – the process that accompanies every movement – in structural engineering can be classified into the categories of harmful, beneficial, or informative vibrations. Vibration is the primary process, the (secondary) effect of which is an acoustic signal in the form of longitudinal sound waves. Vibration and noise processes form the basis of the scientific research field 'vibro-acoustic'. Modern architecture is accompanied by vibro-acoustic phenomena that endanger humans, the environment and their products. Trends in contemporary engineering and technology, coupled with ever-increasing dynamic loads, speeds, weights and minimisation of materials, make an increase in vibration and noise inevitable. These trends, together with the massive application of technological means, pose risks to humans, nature and the technological environment (Uhl, 1997).

In most cases encountered in practice, the analysis of dynamic characteristics is carried out based on the analysis of the behaviour of the structural model. The quality of the analysis depends on the credibility of the model, which is measured by the conformity of the behaviour of the object and the model, both subject to the same type of perturbation. Structural models can be created during analytical transformations used to describe system dynamics or can be based on the results of experiments performed on real objects (Wiliams, Crowley & Vold, 1985).

The analysis of the dynamic properties of structures is mainly carried out by studying the behaviour of a dynamic model of a given structure, which can be done by using analytical descriptions of quantities characterising the dynamics of the system or directly applied to practical experimental methods. Objects are implemented (Żółtowski, 2014).

New tools in this field of research relate to the possible application of modal analysis methods and modern methods of extraction and processing of vibration methods to assess the quality of masonry structures and elements, which is the subject of this work. In practice, they can better understand the behaviour of complex structures, optimise them during design and assess dangerous states. The latter area includes references to the studied problem of finding criteria for the assessment of the state of degradation of old and new brick wall structures and elements, usually those for which the state of failure and the value of the factor of safety are unknown.

Modal analysis is widely used in aeronautical and civil engineering to investigate degradation states and failure locations, modify the dynamics of structures under test, describe and update analysis models and monitor structural vibrations. The following terms can be found in specialised literature: modal analysis, experimental modal analysis and operational modal analysis (Żółtowski & Żółtowski, 2014). Most practical applications of modal analysis require multi-channel experiments and complex calculations associated with processing measured signals and estimating model parameters. The possible applications seen in this way allow distinguishing the following types of modal analysis (Żółtowski & Martinod, 2016):

– theoretical – requires solving the eigenvalue problem for a given structural model of an investigated object;
– experimental – requires controlling the identification experiment during which the object's motion (e.g., vibration) is excited, and measurements of excitation and response are performed in many measuring points;
– operational – based on an experiment carried out in real conditions, during which only the system's response is measured, and the object's motion results from real operational excitations.

SCOPE OF THE EXPERIMENT

The experiment for identifying the destruction state of the studied wall elements is the basic source of information – and on its basis, the value of measures and the structure of the model can be established. The quality of the received model is influenced by the quality of the experimental research findings on the one hand, and the identified model's structure on the other. The modal analysis experiment can be divided into the following stages:

1. Planning:
   - the choice of the way of extorting trembling on the studied elements and the points of application;
   - the choice of points for measuring the trembling and the measuring apparatus;
   - the choice of suitable measuring equipment;
   - the choice of the modelling arrangement (the limitation of the number of degrees of liberty).
2. Calibration of the measuring track.
3. Acquisition and processing of the results.

The studied wall element shows the trembling force of signal extortion proportional to the state of the destruction. The extortion signal and the answer were used for further delimitation of the FRF and the stabilisation diagram.

The equipment necessary for the execution of the experiment of modal analysis consists of the following elements:

- the arrangement for measuring the extortion of movement and the answer;
- the arrangement of signals (the preliminary processing);
- the arrangement for processing and assembling the signals;
- the arrangement for generating the extorting signal;
- the arrangement for arousing the trembling.

As far as service solutions are concerned, the use of signal analysers is the simplest machine but also the most modern, and it offers the greatest possibility of a workstation-specific measurement interface. The basic operation a signal analyser can perform is conventional analogue-to-digital processing, which allows the use of digital techniques when processing modal analysis signals.

In a modal study, it is not important which kinematic quantities are measured. In practice, however, displacement measurements occur in the low-frequency range, while acceleration measurements occur in the high-frequency range. Velocity measurements in structural dynamics studies are known to be best in terms of the RMS value of the shaking velocity obtained by measuring the kinetic energy of the shaking component. However, the sensors that measure displacement and velocity are heavy compared to the materials under study and can affect their behaviour.

The sensors that measure acceleration have a much smaller mass and therefore do not affect the movement of the component. An added benefit of using sensors is that they get a combined acceleration signal of velocity and jerk displacement. Reverse operation depends on differential jitter, which can lead to large errors – especially at higher frequencies. The sensor has a natural resonance, which limits the frequency of use.

The choice of where to install the sensor is crucial as it can affect the results of the modal measurements. Sensors should be mounted so that they do not affect equipment vibrations and should also be fixed at characteristic points of the structure.

Experimental modal analysis requires accurate laboratory conditions for investigation. The model must have known Berg. Extortion can evade these, which they inflict on objects during normal exploitation. When conducting experiments, we may encounter difficulties that correspond to the reality of the conditions onshore: immobilising the research subjects. In the case of large models, performing this experiment is time-consuming.

This paper presents the results of a study of the differentiated states of brick structures obtained by applying experimental modal analysis. For this purpose, the LMS SCADAS Recorder – a device combining the functions of an analyser and a classic recorder, and the Simcenter Testlab (LMS Test.Lab) software for performing the tests and visualising the results were used.

VIBRATIONS IN THE DESCRIPTION OF STRUCTURES

Vibro-acoustics is a domain of science which deals with any vibration, acoustic and pulsation processes occurring in nature, building engineering, technology, machines, devices, communication and transport means (i.e., in the environment). Among the tasks of vibro-acoustics, the following may be rated (Żółtowski, Łukasiewicz & Kałaczyński, 2012):

- the identification of vibro-acoustic energy sources, which consists of location-particular sources within the structure of an object, machine or environment, the determination of their characteristics and mutual relationship, the determination of vibro-acoustic power as well as the character of vibration and sound generation;
- the elaboration of vibro-acoustic energy propagation paths in real structures and environments (buildings, machines, objects, etc.), the theory of energy transmission and transformation, passive and active control means for phenomena, methods for analysing and testing phenomena at the border area between wave and discrete approach;
- the elaboration of control methods for vibro-acoustic energy (emission, propagation) in building structures, machines and environments, and also the elaboration of methods for steering the phenomena is associated with active methods which are presently under development worldwide;
- the use of vibro-acoustic signals for the purposes of technical state diagnostics as they constitute a good carrier of information on the state of an object's destruction as well as the technological process under-way (vibro-acoustic diagnostics);
- the vibro-acoustic synthesis of objects, performed to obtain optimum vibro-acoustic activity (structural, kinematic, dynamic), which covers the synthesis of parameters used in active methods for vibration and noise mitigation, as well as the structural, kinematic and dynamic synthesis of objects and machines;
- the active applications of vibro-acoustic energy to realising various technological processes, beginning from ultrasonic welding and cleaning, transport of materials and machine elements along technological lines, consolidation of moulding sands, shaking out and cleaning castings, ending at the consolidation of soils and different types of concrete.

The vibro-acoustic process may be presented as:

- generation of time-varying forces acting on a structure and its environment;
- propagation and transformation of energy in different environment structures;
- sound radiation through material elements of the environment.

In the analysis of vibro-acoustic processes, the following is taken into account:

- time-space distribution of run of energy coming from a (primary) source;
- response of a system (structure, liquid) as well as energy transmission through propagating media;
- the mutual relationship between sources.

The concept of measurement refers to the process of acquiring and transforming information about what is being measured in order to obtain quantitative results in a form most accessible to the human sensory organs by comparison with units of measurement, converting it into space or time (recording), mathematical processing or go to the application.

To make such measurements (Żółtowski & Żółtowski, 2014) are necessary:

- determining the time course of vibrations and their parameters to determine vibration types, characteristic sizes and perform detailed analysis; determining of time runs of vibrations and their parameters to determine the kinds of vibrations, their characteristic quantities and to perform a detailed analysis;
- finding vibration sources and places of their occurrence;
- determining characteristic features of systems (e.g., determining loads during vibrations and their dependence on an object's parameters, its shape, dimensions, material properties, etc.);
- minimising vibrations harmful to the reliable operation of devices and their human operators;
- determining harmfulness level of occurring vibrations and implementing preventive measures.

In practice, vibration signals are more commonly used than noise signals because of their ease of transmission and accurate measurement (Żółtowski & Żółtowski, 2014).

The system vibration in which the equilibrium state of an object is disturbed and moves under the action of elastic force, gravity or friction is called free vibration. In a system with one-degree of freedom (1-DOF), the disturbance of the equilibrium state is characterised by initial conditions: initial position (x_0) and initial velocity (v_0). If a system consists of 1-DOF (Fig. 1) – i.e., single mass (m), and linear properties of elasticity (k) and damping (c), with a harmonic excitation force $F(t)$ acting on it – then its equation of motion is expressed by the following formula:

$$m\overset{**}{x} + c\overset{*}{x} + kx = F(t), \tag{1}$$

which represents the equation of harmonic vibrations or harmonic oscillator vibrations.

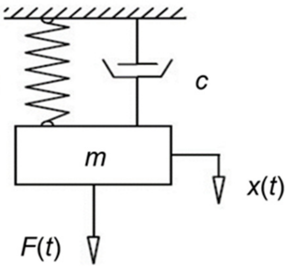

Fig. 1. One-degree-of-freedom system to perform translation motion

Source: own work.

As a result of it, natural vibration of the 1-DOF system is entirely determined by natural frequency of vibration. The amplitude of the vibration depends on initial conditions but natural frequencies and the vibration period do not depend on them. The solution of the equation (i.e., translation) takes the following form:

$$x = A\sin(\omega_0 t + \phi). \tag{2}$$

By differentiating this equation, the vibration velocity is obtained:

$$\overset{*}{x} = A\omega_0 \cos(\omega_0 t + \phi), \tag{3}$$

which is also a periodical function of time, of the same period as that of translation. By differentiating the velocity equation, the value of vibration acceleration is obtained:

$$\overset{**}{x} = -A\omega_0^2 \sin(\omega_0 t + \phi) = -{\omega_0}^2 x. \tag{4}$$

It is a periodical function of time, the same period as translation and velocity. Acceleration is proportional to translation and directed against it (i.e., it always is pointing position of equilibrium).

The parameters a, v and x are those of the vibration process, which proves that the vibrations properly describe the state of the structure.

In the low-frequency range, building structures can be modelled by using discrete systems of a few DOFs – and rather often – a 1-DOF system. In contrast to continuous one, the discrete system is characterised by point distribution of mass, stiffness and damping and dimensions of the elements do not play any role. The number of DOFs determines the number of independent coordinates which should be introduced to get an unambiguous description of the system's motion (the number of DOFs is equal to the number of mass elements in the system in question). In practice, the system presented in Figure 1 can model:

– the building machine of mass (m), seated on shock absorbers (k, c) and fastened to a big mass foundation;
– the work machine of mass (m), seated on shock absorbers (k, c) and moving along an even road;
– the high building structure (high chimney, mast) under wind action.

The output signal received at any structural point is the weighted sum of the responses to all elementary events (t, w, r) that occur at some point in the dynamical system with the momentum transfer function $h(t, \theta, r)$. These effects add up with additional transformations along different reference axes, and changes in the signal reception point (r) are also associated with changes in transmittance.

The vibration signal transmission model through the test structure or wall element is actually described by the FRF, which is determined by the experimental modal analysis in the form of the ratio of the vibration excitation force to the amplitude of the vibration acceleration at the output. Permeability $H(f)$ is defined as the response to the excitation ratio, which is the reciprocal of the FRF. The indicated properties of the elaborated model of signal transition through tested materials were further used for assessing changes in the degree of degradation of structures or brick wall elements during the testing transition of vibration signals through various structures of brick wall elements and segments.

A modal analysis is widely applied for removing damages resulting from vibrations, modifying structure dynamics, updating analytical models or state control, and is also used for monitoring vibrations in the aircraft industry and civil engineering (Stępniewski et al., 2013).

$$\varpi = [\varpi_1,\ \varpi_2,\ \ldots,\ \varpi_n]. \qquad (5)$$

The theoretical modal analysis is mainly used in the design process (i.e., when it is not possible to perform tests on objects). The traditional experimental modal analysis (EAM) makes use of input (excitation) to output (response) relation, and it is measured to assess modal parameters consisting of modal frequencies and damping. However, the traditional EAM has some limitations, such as:

– in the traditional EAM, artificial excitation is used to measure vibration frequencies;
– the traditional EAM is usually performed in laboratory conditions.

However, in many cases, a real state of degradation may greatly differ from those observed in a laboratory environment. In experimental modal analysis, the identification experiment consists of exciting the object's vibrations at simultaneous measuring excitation forces, and the system's response is usually in the form of vibration acceleration amplitude.

RESULTS AND DISCUSSION

The measurement equipment for measuring the frequency response function is used to measure the wave shape and the response system and determine the most commonly used functions. Using Simcenter Testlab software (Fig. 2), you can easily perform modal analysis on brick elements and other building structures.

A fit and a damaged brick were measured from a large group of building materials to compare their fitness. Figure 3 shows the results obtained after performing measurements on axis Y because, in brick walls, compressive strength can be most destructive.

For a better visualisation of the results of the investigation, the results are shown separately (Fig. 4)

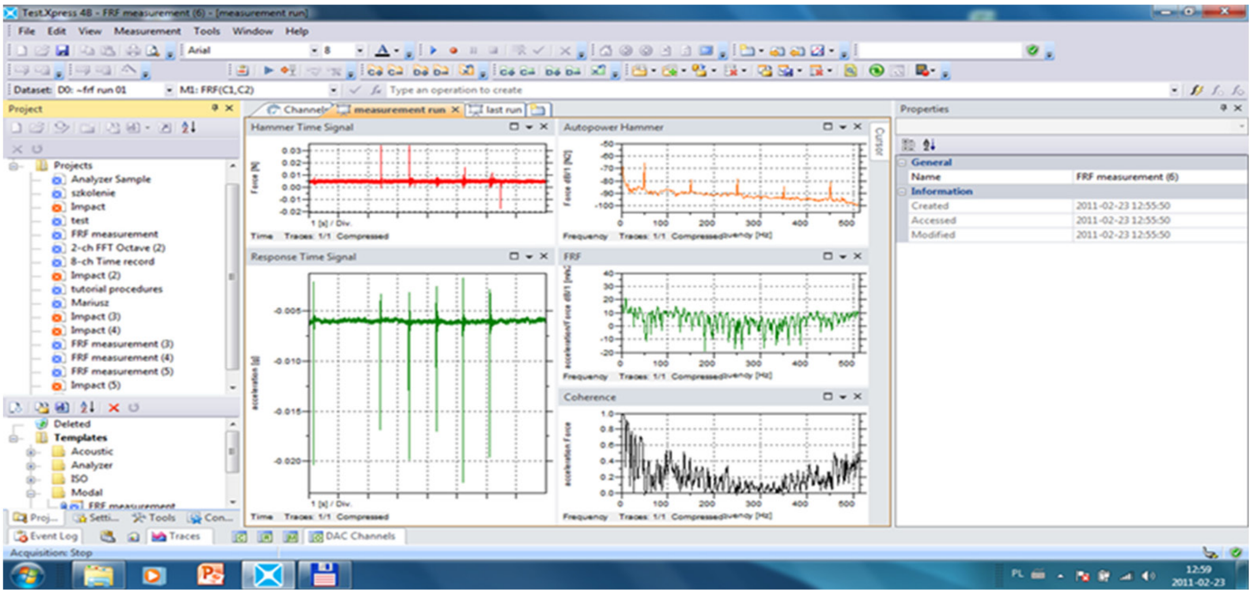

Fig. 2. Software front panel

Source: ©Siemens Simcenter Testlab software.

– five times is shown the FRF for good, and five times for destroyed brick element. In Figure 4, the extortion and the answer of signal in time domain that allows gaining FRF is shown (once).

Graphic results, which show FRF of good and destroyed bricks measured in axis Y, are shown in Figure 5 – five measurements for each material sample.

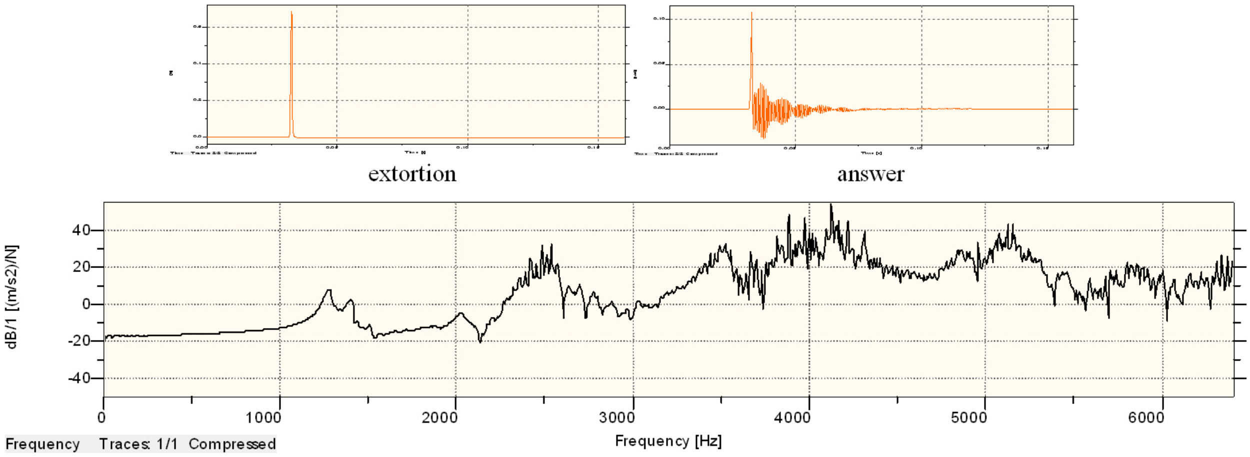

Fig. 3. Example exposition of results of measurement – own study

Source: own tests performed with the Simcenter Testlab software.

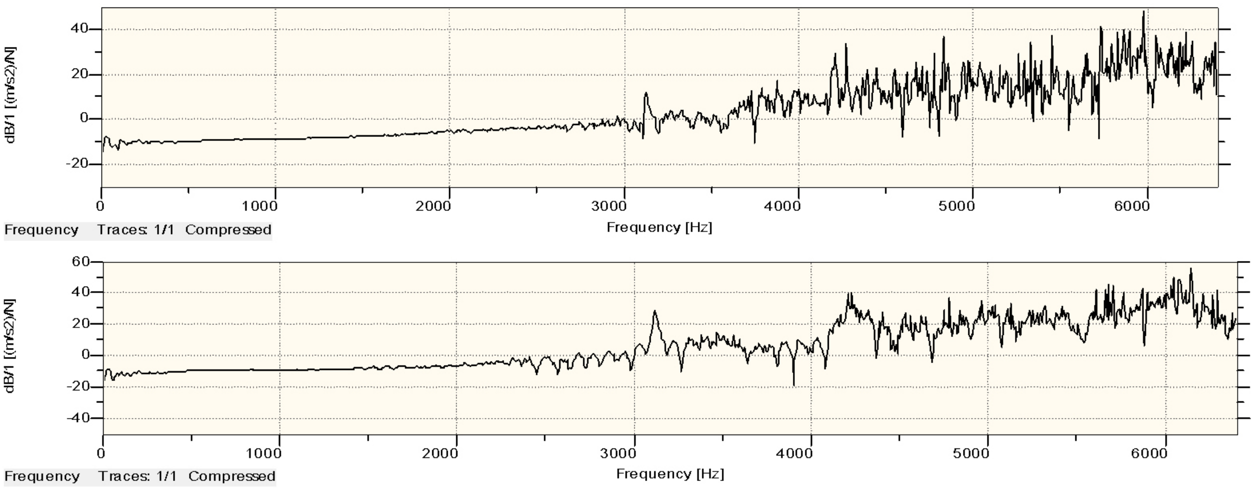

Fig. 4. Composition of results of measurements (the temporary course of extortion, temporary course of answer, the FRF) the full brick in axis Y

Source: own tests performed with the Simcenter Testlab software.

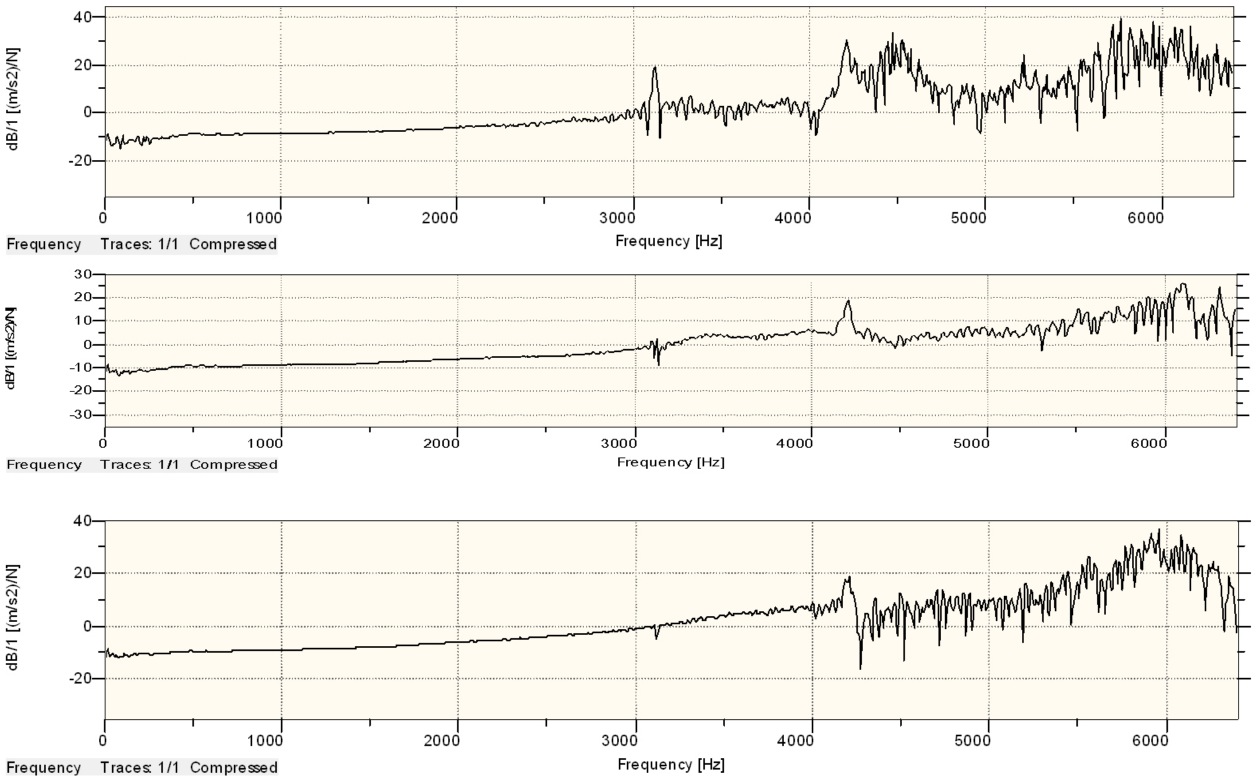

Fig. 4. (cont.)

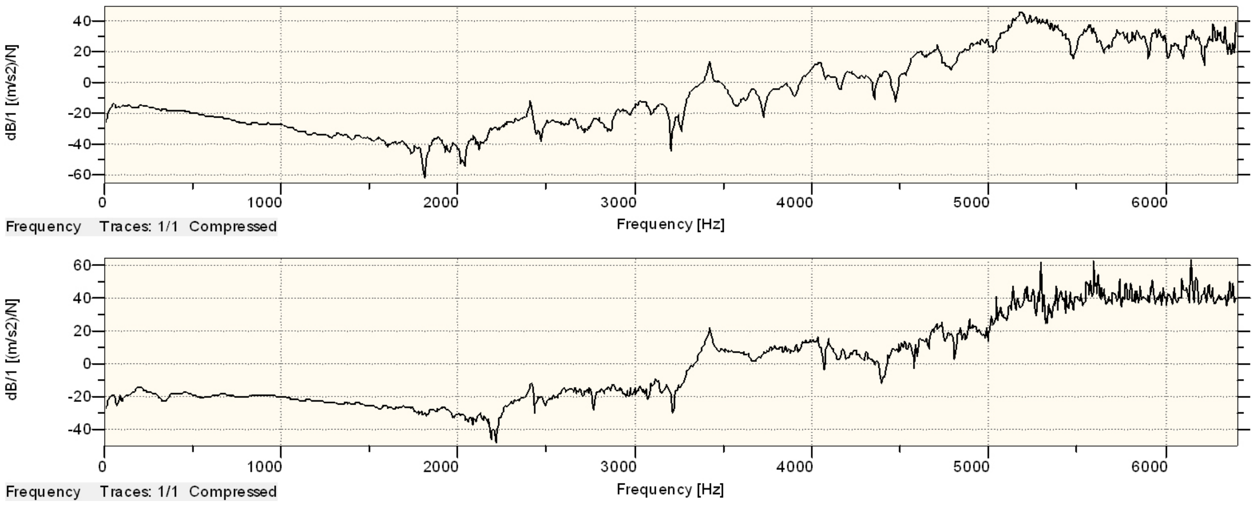

Fig. 5. Composition of FRF of destroyed full brick in axis Y

Source: own tests performed with the Simcenter Testlab software.

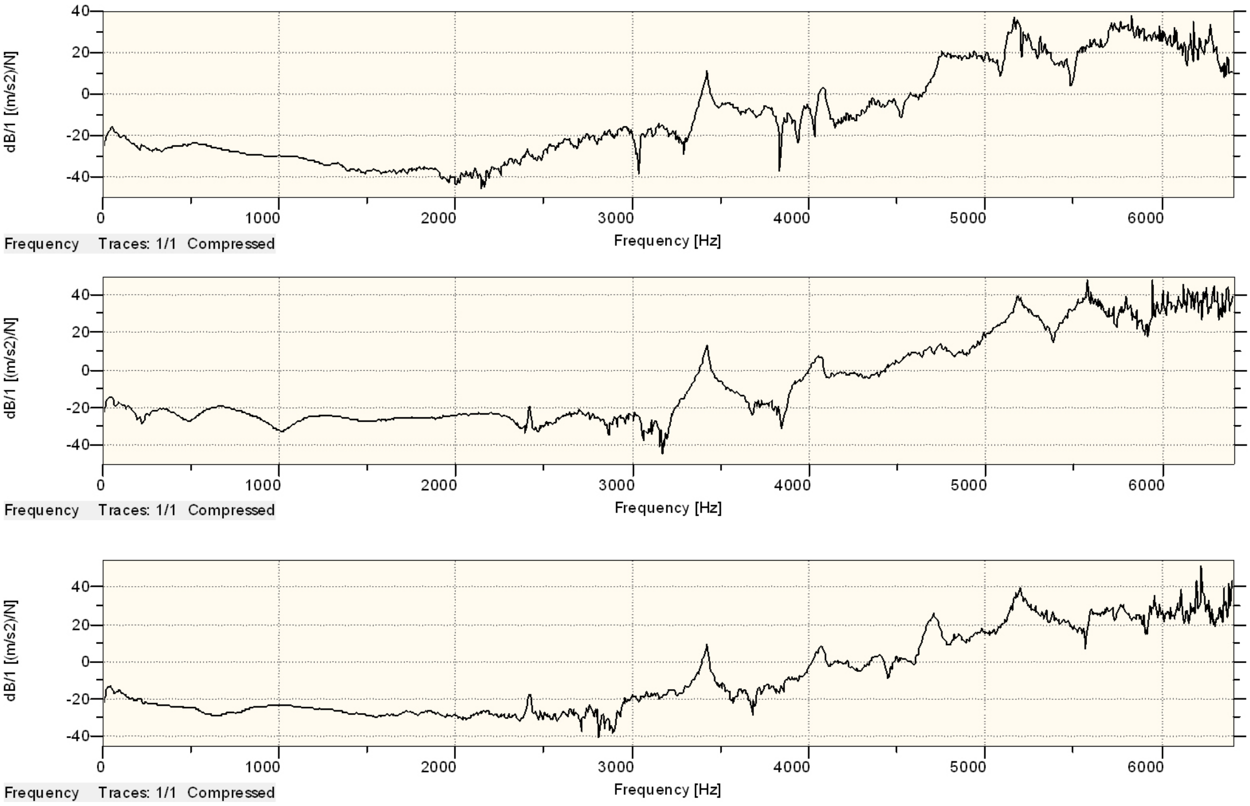

Fig. 5. (cont.)

CONCLUSIONS

The results point to the fact that it is possible to distinguish between material properties, which impacts the ability to distinguish between their mechanical properties. The study also confirmed the usefulness of the LMS test apparatus using operational modal analysis performed on the actual building construction.

By obtaining graphical charts of FRF, and later their comparison, it is possible to observe their diversity. These charts are different for materials that are in good and damaged condition, which demonstrates the ability to assess the destruction of a brick element.

The graphical course of the FRF for damaged elements has a significantly different course than the graphical presentation of the FRF for remote elements, which allows clearly determining whether the tested element is damaged or not. The damage is clearly manifested by the undulation of the function arising at the level of 2,000 Hz, while the serviceable elements show the undulation at the level between 3,000–4,000 Hz.

It practically verified the sensitivity of the assessment of modal analysis to the degree of brick structure degradation. It becomes possible to determine hazards to a building structure based on examining values of frequencies.

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POMIAR DRGAŃ W BADANIU DEGRADACJI MATERIAŁÓW BUDOWLANYCH

STRESZCZENIE

Obiekty ceglane podlegają dużym obciążeniom dynamicznym, czego rezultatem są procesy wibracyjne. Drgania mogą wpływać na stan zdatności użytkowej obiektów poprzez zmniejszenie komfortu pracy użytkowników, a także możliwe osiągnięcie poziomu zagrażającego bezpieczeństwu obiektów. Oddziaływanie drgań na konstrukcję objawia się głównie dodatkowymi naprężeniami w danym przekroju poprzecznym, które sumują się z wynikającymi z obciążeń statycznych. Obciążenia dynamiczne mogą powodować niszczące skutki w budynkach o różnych typach konstrukcyjnych, a nawet prowadzić do ich zniszczenia. W artykule opisano serię autorskich analiz procesu niszczenia wybranych obiektów murowanych metodą eksperymentalnej analizy modalnej. Badania przeprowadzono w celu udoskonalenia oceny jakości konstrukcji budowlanych pod kątem stanu technicznego konstrukcji murowanych oraz spełnienia parametrów bezpieczeństwa.

Słowa kluczowe: analiza modalna, częstotliwość drgań własnych, wykres stabilizacji, drgania konstrukcji

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EVALUATION OF THE INFLUENCE OF LINEAR STRESS CONCENTRATORS IN REINFORCED CONCRETE ELEMENTS USING THE POSTULATES OF FRACTURE MECHANICS

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ABSTRACT

The article is devoted to the study of linear stress concentrators in reinforced concrete, which, unlike randomly located stress concentrators from a large and medium-sized concrete aggregate (granite or gravel crushed stone), can have a strategic impact on the formation of cracks in a reinforced concrete element in the presence of a sufficient level of tensile stresses. The study is one of the theoretical parts of a significant research program on the cracking of reinforced concrete elements in tension and bending. The description of the process of cracking with the help of fracture mechanics allows us to try to formulate a mathematical apparatus for taking into account stress concentrators linearly located in reinforced concrete elements and their influence on the formation of cracks, in particular, at the moment of cracking in bending elements. Field tests of specimens with artificially created stress concentrators were carried out, including the RILEM method, on the basis of which trial calculations of the cracking moment were carried out using the stress intensity factor.

Keywords: fracture mechanics, the stress intensity factor, cracking moment

INTRODUCTION

The concentration of stresses in concrete, according to the studies of Bažant and other researchers according to the basics of fracture mechanics, occurs in places where there are pores, cavities, and areas with increased or decreased strength. In the works of Bressan, Effting and Tramontin (1991) and the work of Golewski and Sadowski (2007, 2010), it is indicated that in a reinforced concrete element, micro-cracks appear at the contact edge of the aggregate and the concrete mass during stretching (Fig. 1). However, the aggregate is chaotic in the concrete and therefore, at certain stages of loading, micro-cracks do not develop into main cracks, because the mass of concrete prevents the development of these micro-cracks, as stated in the papers by Hillerborg, Modéer and Petersson (1976), the American Concrete Institute (ACI Committee 446, 1992; ACI Committee 224, 1997; Committee 224, 2001), Bažant (1992), Prokopski (2009), and Bažant and Cedolin (2010).

As confirmed by the research conducted earlier by Salauyou (2009), Knyziak and Salauyou (2010), Salauyou and Knyziak (2010a, 2010b), the spacing of cross-section bars of horizontal meshes and skeletons affects the spacing of cracks in reinforced concrete elements in tension and bending. This phenomenon has also been described in studies by Lee, Mansur, Tan and Kasiraju (1964, 1987), and Nawy (1964). The mechanism of crack formation at the location of the cross-section bars can be described by means of fracture mechanics.

The cross-section bar placed in the concrete differs from the aggregate in that it occupies a specific,

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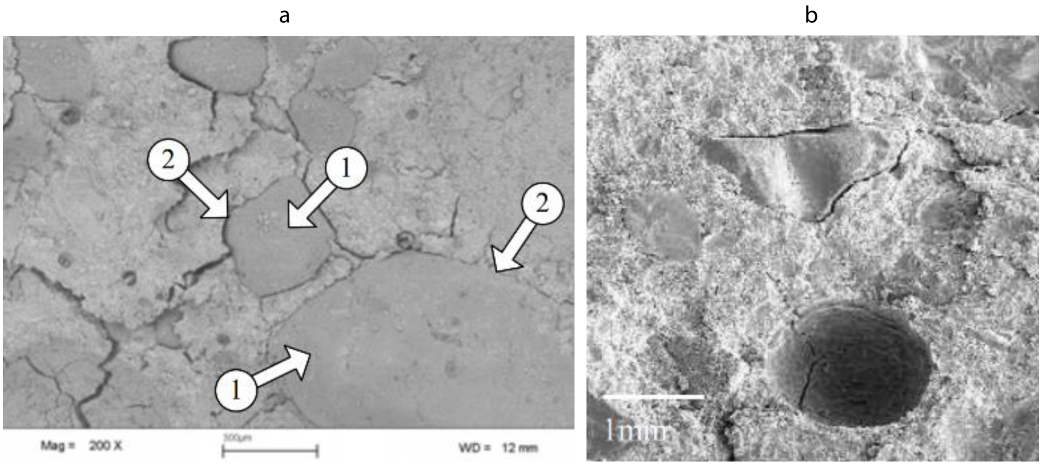

Fig. 1. Micro-cracks appear at the contact edge of the aggregate and the concrete mass: 1 – aggregate grains, 2 – micro-cracks in contact layers

Source: [a]Golewski and Sadowski (2007); [b]Bressan, Effting and Tramontin (1991).

linearly oriented position in the concrete (a position perpendicular to the bending moment while bending elements). When tensile stress appears and increases in concrete, micro-cracks appear on the edge of the cross-section bar and concrete mass, as well as on the edge of aggregate and concrete mass. With a further increase in tensile stresses in the concrete, micro-cracks develop along the entire boundary of the bar with the concrete, and the cross-section bar loses its cohesion with the concrete. This means that in the concrete at the location of the cross-section bar, there is a weakening equal to its diameter (Fig. 2).

If the cross-section is weakened with a circular or elliptical hole, then, according to the Inglis equation (1913), the stress concentration factor $K = 1 + 2a / b$ (a and b are radii of the horizontal and vertical axes, respectively) is applied to the elliptical cross-section in tension. Accordingly, for a circle, the $K = 3$. In fur-

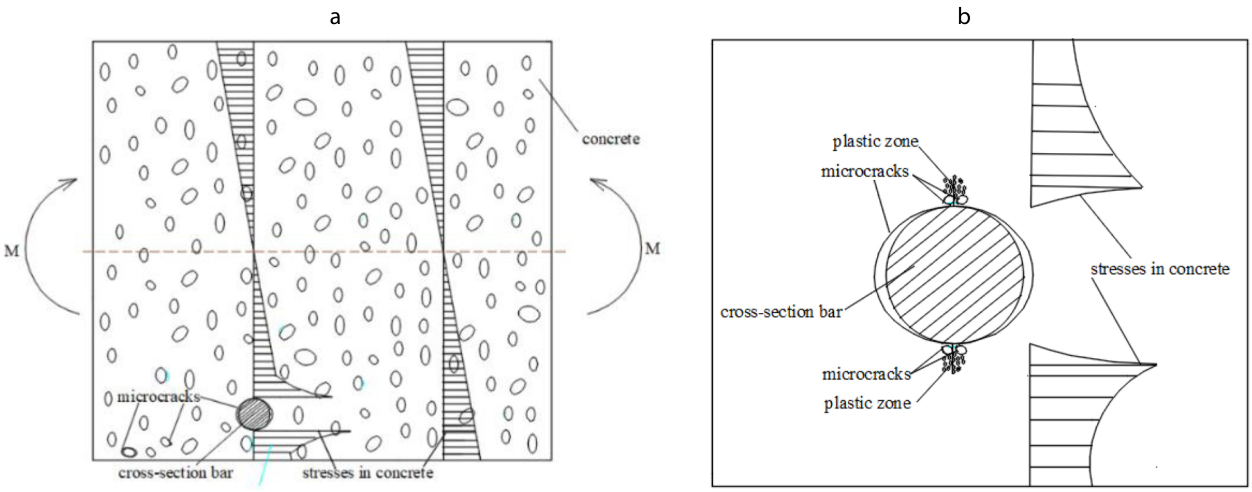

Fig. 2. Tensile stresses in concrete. The appearance of the initial crack in the fracture process zone near the linear stress concentrator transverse reinforcing bar

Source: [a]Salauyou (2009); [b]Salauyou and Knyziak (2010).

ther research, the researchers found that a $K = 3$ is correct for a very wide plane and that stress concentration factors are determined by empirical testing for narrow planes. Table 1 presents the values of the stress concentration factor depending on the ratio of the opening width to the width of the plane.

Table 1. The value of the stress concentration factor (K) depending on the scale of the hole to the width of the plane

The size of the scale of the hole to the width of plane	0	0.1	0.2	0.3	0.4	0.5
The magnitude of the stress concentration factor	3.00	3.03	3.14	3.36	3.74	4.32

Source: calculated with using Kirsch equations.

This means that the stress concentration in the concrete next to the cross-section bar is more than three times that of the stress in the cross-section of the concrete without weakening and that an initial crack will necessarily be formed at the location of the cross-section bar (Fig. 2).

For concrete, as for a non-homogeneous material, special coefficients can be applied that describe the stress concentration at the crack tip. For a crack of normal separation, which are cracks normal to the longitudinal axis of the element from the action of a bending moment, such a coefficient is K^s_{Ic}, determined empirically by testing samples, according to the RILEM methodology.

The equation is used for the determination of K^s_{Ic} in the work of Karihaloo (1995):

$$K^s_{Ic} = 6Y(\alpha)\, M_{cr}\, a^{0.5} / b\, d^2,$$

$$M_{cr} = K^s_{Ic}\, b\, d^2 / 6Y(\alpha)\, a^{0.5},$$

where:
$Y(\alpha)$ – geometric function.

For a beam or slab freely supported with one load point:

$$Y(\alpha) = [1.99 - \alpha(1 - \alpha)\,(2.15 - 3.93\alpha + 2.7\alpha^2] / [(1 + 2\alpha)\,(1 - \alpha)^{3/2}].$$

For a beam or slab freely supported with two load points:

$$Y(\alpha) = 1.99 - 2.47\alpha + 12.97\alpha^2 - 23.17\alpha^3 + 24.8\alpha^4 + 60.5\alpha^{16},$$

$$\alpha = a / d,$$

$$M = M_1 + M_2,$$

where:
M_1 – bending moment from the applied load,
M_2 – bending moment of self-weight action,
a – initial notch (in the RILEM method), equal to the length of the initial crack.

In this way, knowing K^s_{Ic} (if there is a possibility to determine it through material tests for a given concrete), we can approximately calculate M_{cr}.

EXPERIMENTAL ELEMENTS AND TESTING PROCEDURE

Nine reinforced concrete beams with dimensions of 1,200 × 250 × 150 mm were used with the reinforcement of 12 mm diameter S500 bars. All of them are from concrete classes 25/30. A description of experimental elements (experimental beams), with dimensions of 1,200 mm long, 250 mm thick and 150 mm wide, is presented in Table 2. The design of the beams differed: three elements with a cross-section bar, and three elements with a through hole instead of a cross-section bar, and three control elements (without any cross-sectional weakness). The central zone of the beams is shown in Figure 3.

Table 2. Experimental elements/beams

No	Pattern code	Peculiarities of the pattern
1	B 1-1	with a cross-section bar
2	B 1-2	with a cross-section bar
3	B 1-3	with a cross-section bar
4	B 2-1	with a hole instead of a cross-section bar
5	B 2-2	with a hole instead of a cross-section bar
6	B 2-3	with a hole instead of a cross-section bar
7	B 3-1	without any cross-sectional weakness
8	B 3-2	without any cross-sectional weakness
9	B 3-3	without any cross-sectional weakness

Source: own work.

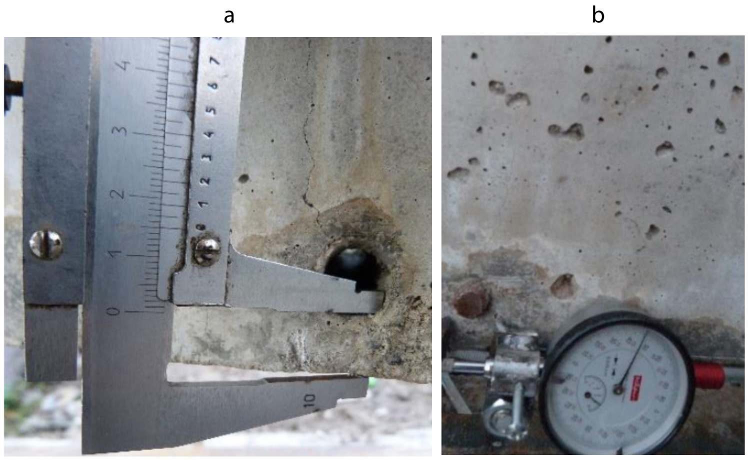

Fig. 3. Beams with a hole instead of a cross-section bar (a) and beams with a cross-section bar (b)

Source: own work.

All the experimental elements/beams were tested in the same way for bending on a special test stand with the help of a hydraulic cylinder. Figure 4 shows the research scheme and the view of the test stand. During the experiment, the deflection of the beams and the width of the cracks were measured. The width of the cracks was determined using a clock-type indicator (with a measuring accuracy of 0.001 mm) set on special holders and an optical microscope. The deflection of the beams was measured using a clock--type indicator with an accuracy of 0.01 mm, set on a special frame.

Also, four concrete beams (concrete classes 25/30) with dimensions of 1200 × 250 × 150 mm with a special notch were made and tested according to the RILEM method in order to determine the coefficient K_{Ic} that characterises the normal detachment crack according to the fracture mechanics approach. Figure 5 shows the beams for testing according to the RILEM method, during and after testing.

The beams were tested in the same way for bending on a special test bench using hydraulic cylinders according to the RILEM method (three load – unload cycles). Figure 6 shows the research scheme and the

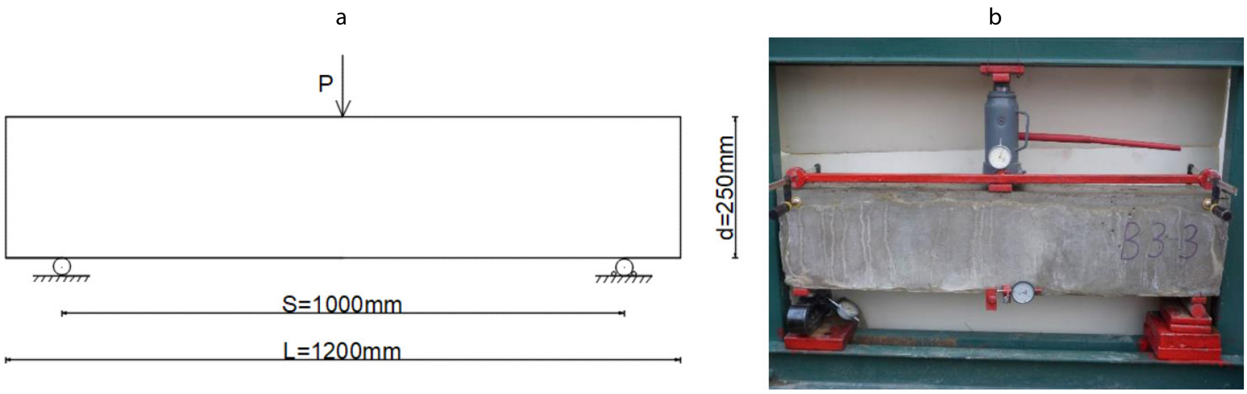

Fig. 4. Scheme of conducting tests, including for determining the coefficient K_{Ic}, according to the RILEM method (a); view of the test stand (b)

Source: own work.

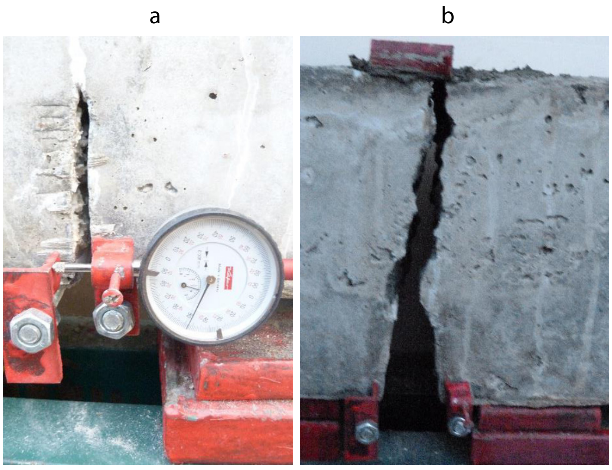

Fig. 5. Beams for testing, according to the RILEM method, the during the test (a) and after testing (b)

Source: own work.

Fig. 6. Scheme of testing of four experimental elements/beams, according to the RILEM method (a); view of the test stand (b)

Source: own work.

view of the test stand. During the experiment, the width of the cracks was determined using a clock-type indicator (with a measuring accuracy of 0.001 mm) set on special holders.

RESULTS AND DISCUSSION

As a result of testing beam samples according to the RILEM method, it was possible to obtain the relevant data necessary to determine the stress intensity factor (K_{Ic}). A characteristic diagram of the dependence of deformations from the load measured in the centre of the beam directly in the zone of artificial damage to the section using a dial indicator with a division value of 0.001 mm is shown in Figure 7.

Young's modulus (E) is calculated from the equation (Shah & Carpinteri, 1991):

$$E = 6S\, a_0\, V_1(\alpha) \,/\, (C_i\, d^2\, b);\ \alpha = a_0 / d = 1/3;$$
$$C_i = 2.8\ 10^{-9}\ \mathrm{m{\cdot}N^{-1}};\ d = 0.25\ \mathrm{m};\ b = 0.15\ \mathrm{m},$$

$$V_1(\alpha) = 0.76 - 2.28\alpha + 3.87\alpha^2 - 2.04\alpha^3 + 0.66 / (1 - \alpha)^2 = $$
$$= 1.83944;\ E = 34.896.8\ \mathrm{mPa}.$$

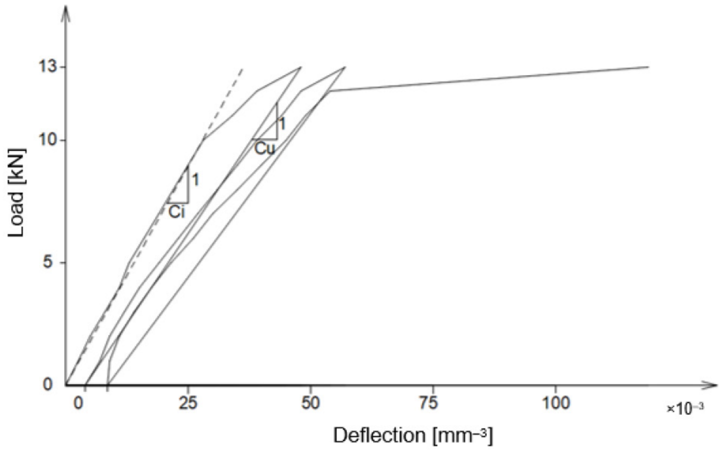

Fig. 7. Dependence of deformations from the load according to the RILEM method

Source: own work.

The critical effective crack length $a_c = a_0$ + stable crack growth at peak load:

$a_c = E\ C_u\ d^2\ b\ /\ [6S\ V_1(\alpha)]$; $C_u = 3.38461 \cdot 10^{-9}\ \text{m} \cdot \text{N}^{-1}$; $a_c = 0.100329$ m.

The critical stress intensity factor $K^s_{Ic} = 3(P_{max} + 0.5W)\ S(\pi\ a_c)^{0.5}\ F(\alpha_1)\ /\ (2\ d^2\ b)$:

$P_{max} = 13{,}000$ N, $W = W_0 S\ /\ L$, W_0 – self-weight of the beam = 1,102.5 N, $\alpha_1 = a_c\ /\ d = 0.401316$,

$$F(\alpha_1) = 1.99 - \alpha_1(1 - \alpha_1)\ (2.15 - 3.93\alpha_1 + 2.7\alpha_1)\ /\ [\pi^{0.5}(1 + 2\alpha_1)\ (1 - \alpha_1)]^{1.5} = 1.43673,$$

$K^s_{Ic} = 1.735159\ \text{mPa} \cdot \text{m}^{0.5}$.

The analysis of the test results of 9 experimental element/beams showed that the failure of all elements occurred at the same value of the bending moment (13 kNm). The magnitude of the cracking moment for all three elements with a cross-section bar was three elements with through hole 7 kNm. The value of the cracking moment for all s was also 7 kNm. The value of the cracking moment for all three control elements (without a cross-section bar and without a hole) was 10 kNm. Figure 8 shows the elements during the tests, after cracking.

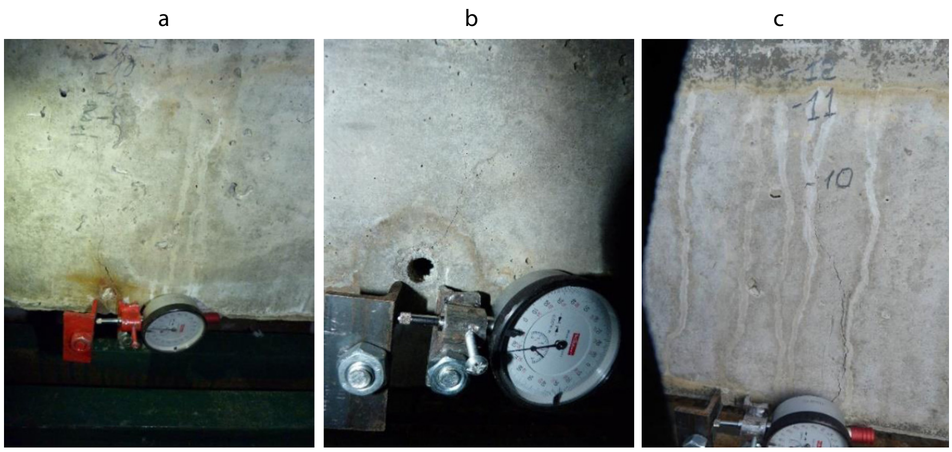

Fig. 8. Cracking of beams – with a cross-section bar (a), with a through hole instead of a cross-section bar (b), without a cross-section bar and without a hole (c)

Source: own work.

We determine the moment of cracking for beams with a transverse rod and beams with a through hole analytically according to the formulas indicated in the Karihaloo (1995) for a notched beam with free support. For the height of the notch, we take the upper point of the transverse rod or the upper point of the through hole (we accept this assumption, taking into account the fact that the thickness of the concrete cover between a through hole or rebar and the surface of a reinforced concrete element is 15 mm, which is less than the maximum size of large concrete aggregate and less than stable crack growth at peak load):

$a = 27$ mm, $\alpha = a / d = 27$ mm / 250 mm = 0.108,

$$Y(\alpha) = [1.99 - \alpha(1 - \alpha)\ (2.15 - 3.93\alpha + 2.7\alpha^2)] / [(1 + 2\alpha)\ (1 - \alpha)^{3/2}],$$

$$Y(\alpha) = [1.99 - 0.108(1 - 0.108)\ (2.15 - 3.93 \cdot 0.108 + 2.7 \times 0.108^2)] / [(1 - 2 \cdot 0.108)\ (1 - 0.108)^{3/2}] = 1.7773186,$$

$$M_{cr} = (K^s_{Ic}\ b\ d^2) / (6Y(\alpha)\ \text{a}^{0.5}) = (1.735159\ \text{mPa}\cdot\text{m}^{0.5} \times 0.15 \cdot 0.25^2) / (6 \cdot 1.7773186 \cdot 0.027^{0.5}),$$

$$M_{cr} = 9{,}283.5\ \text{kNm};\ M_{cr} = (M_1 + M_2),$$

$$M_1 = M_c - M_2;\ M_2 = (W / 2)\ (S / 2);\ W = W_0 S / L,$$

where:

M – bending moment of external load,

M_1 – bending moment from applied load, M_1 = 9,283.5 kNm – (1,102.5 · 1/2 1.2) (1/2) = 9,053.8 kNm,

W_0 – self-weight of the beam, W_0 = 1,102.5 N.

The analytically calculated moment of cracking is somewhat different from the actual value of the moment from the applied load at which a crack was formed in samples with a transverse reinforcing bar and in samples with a through hole (7 kNm); therefore, the mathematical apparatus needs to be improved and refined. But in view of the fact that the calculated moment we received is less than the moment of cracking of control samples (without damage to the section) – 10 kNm, this confirms the correctness of the general direction of theoretical research to determine the moment of cracking of the section of a reinforced concrete element with transverse reinforcing bars with the help of fracture mechanics postulates.

CONCLUSIONS

As a result of the studies carried out, it was possible to obtain the relevant values of the stress intensity factor (K_{Ic}) according to the RILEM methodology. These data will be used in the future to develop and test a mathematical apparatus for the analytical calculation of the bending moment of cracking for reinforced concrete elements with linear section damage located perpendicular to the longitudinal axis, including at the location of transverse reinforcement bars.

Experimental studies confirmed the theories about the inevitability of cracks at the location of the cross-section bars and about the impact of the presence of the cross-section bars on the magnitude of the cracking moment.

As a result of bending tests of nine reinforced concrete beams, it was confirmed that cracks always appeared in the place of placing the cross-section bars or in the place of placing the through hole, and with the same value of the cracking moment (30% lower than in the control elements), which confirms the theories that the presence of a cross-section bar causes stress concentrations in the concrete, as well as the presence of a through hole of the same diameter.

Authors' contributions

Conceptualisation: D.S. and P.K.; methodology: D.S.; formal analysis: D.S. and P.K.; investigation: D.S.; recourses D.S.; data curation D.S.; writing – original draft preparation: D.S. and P.K.; writing – review and editing: D.S. and P.K.; visualization: D.S.

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

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OCENA WPŁYWU LINIOWYCH KONCENTRATORÓW NAPRĘŻEŃ W ELEMENTACH ŻELBETOWYCH Z WYKORZYSTANIEM POSTULATÓW MECHANIKI PĘKANIA

STRESZCZENIE

Artykuł poświęcono badaniu liniowych koncentratorów naprężeń w żelbecie, które w przeciwieństwie do losowo rozmieszczonych koncentratorów naprężeń z dużego i średniego kruszywa betonowego (tłuczeń granitowy lub żwirowy) mogą mieć istotny wpływ na powstawanie spękań w elemencie żelbetowym w przypadku wystarczającego poziomu naprężeń rozciągających. Praca jest jedną z teoretycznych części znaczącego programu badawczego dotyczącego pękania przy rozciąganiu i zginaniu elementów żelbetowych. Opis procesu pękania za pomocą mechaniki pękania pozwala na próbę sformułowania aparatu matematycznego uwzględniającego koncentratory naprężeń liniowo rozmieszczone w elementach żelbetowych i ich wpływ na powstawanie rys, w szczególności w momencie pękania elementów zginanych. Przeprowadzono badania terenowe próbek ze sztucznie wytworzonymi koncentratorami naprężeń, w tym metodą RILEM, na podstawie których przeprowadzono próbne obliczenia momentu pękającego z wykorzystaniem współczynnika intensywności naprężeń.

Słowa kluczowe: mechanika pękania, współczynnik intensywności naprężeń, moment rysujący

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ORIGINAL PAPER

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ASSESSMENT OF SELECTED LANDFILL IMPACTS ON SELECTED SEGMENTS OF THE ENVIRONMENT – A CASE STUDY

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ABSTRACT

Landfilling is the oldest method of waste management. A number of biological, chemical, and physical reactions occur at the landfills, which cause a threat to the environment. For this reason, landfill monitoring is necessary, and biomonitoring is increasingly beginning to be used. The aim of this study is to (i) determine some effects of the landfill on the surrounding environment, (ii) analysis of plant bioindicators and (iii) biomonitoring based on the occurrence of plant species producing allergenic pollen. Furthermore, plants producing fruits and seeds were also analysed. During biomonitoring, no serious effects of the landfill on the surrounding environment were detected. The plant species found were evaluated based on the frequency of occurrence, pollination vector, distribution of fruits and seeds, and intensity of allergen effects. Thanks to the occurrence of plant allergens, there is a potential risk of the spread of allergens to the landfill surroundings. Furthermore, some species of non-native and invasive plants were found on the active part of the landfill. These species spread their seeds and fruits, and they pose a potential risk to the ecosystems.

Keywords: municipal solid waste, landfill impact, biomonitoring

INTRODUCTION

Landfilling as a method of waste management

The growing human population and the growth of consumer lifestyles place ever-greater demands on waste management (WM), (Das et al., 2019; Noor et al., 2020; Kurniawan et al., 2021). Landfilling is one of the oldest waste management methods (Adamcová, 2019; Sadhasivam, Sheik Mohideen & Alankar, 2020) and the dominant waste disposal method (Ma et al., 2022); however, there are increasing efforts to develop other waste disposal methods. Above all, this concerns the energy use of waste and recycling (Hahladakis & Iacovidou, 2019; Mukherjee, Denney, Mbonimpa, Slagley & Bhowmik, 2020; Shah, Srivastava, Mohanty & Varjani, 2021). Despite the development of other waste disposal methods, the current state allows concluding that some waste will always be disposed of in landfills (Vaverková, 2019). For example, the bottom ash generated during energy utilisation of waste (incineration) is further landfilled (Kumar & Singh, 2021; Nag & Shimaoka, 2023). Therefore, the attention is now shifting to the so-called circular economy. In this context, emphasis is placed on minimising waste production and maximising the use of waste (Fogarassy & Finger, 2020; Kern, Sharp & Hachmann, 2020). One of the main reasons why landfilling is among the most used waste disposal methods is its relatively low price for disposal – economic advantages (Vaverková, 2019; Liu, Liu & Wang, 2020).

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Landfill impact on the environment

A number of biological, chemical, and physical reactions occur at the landfill sites, which cause a potential threat to the environment (Vaverková, 2019; Nanda & Berruti, 2021). This is primarily due to the creation of leachate and landfill gas (Vaverková, 2019; Shammas, Wang, Wang & Chen, 2020; Rasapoor, Young, Brar & Baroutian, 2021). These two factors can negatively affect the surroundings of the landfill (Podlasek, Jakimiuk, Vaverkova & Koda, 2021; Winkler et al., 2021; Koda et al., 2022; Vaverková et al., 2022). Although nowadays landfills are designed and operated in such a way as to eliminate this risk, the problem lies in the lifetime of the landfill, which is many times longer than the operation of the landfill (Madon et al., 2019; Kamaruddin et al., 2021). It means that the landfill is active for a long time, even after it is closed and reclaimed (Madon, Drev & Likar, 2019; Abiriga, Jenkins, Vestgarden & Klempe, 2021). Thus, a landfill is a continuous potential source of environmental pollution that is passed on to future generations.

Monitoring of landfills with particular emphasis on biomonitoring

Landfill monitoring is necessary after the closure of a landfill, and in recent years, the interest of the scientific community in issues related to the responses of living organisms to the emitted pollutants – the so-called biomonitoring – is growing (Rumbold & Mihalik, 2002; Winkler et al., 2021; Jafarova, Contardo, Aherne & Loppi, 2022; Koda et al., 2022; Vaverková et al., 2022). Plant reactions are manifested, for example, by changes in behaviour, appearance, or frequency of occurrence (Winkler et al., 2021; Koda et al., 2022; Vaverková et al., 2022). Thanks to this, possible negative environmental effects can be recognised early on, and thus solved. For these reasons, the importance of biomonitoring is not negligible and thanks to it, the presence and source of contaminants in the monitored environment can be detected and evaluated. Therefore, the aim of this study is to (i) determine the impact of a selected landfill on the surrounding environment, (ii) analysis of plant bioindicators and (iii) biomonitoring based on the occurrence of plant species producing pollen as an allergen. Furthermore, plants producing fruits and seeds that can spread unchecked into surrounding ecosystems were also analysed.

MATERIAL AND METHODS

Landfill site description

The Zdounky-Kuchyňky landfill (49.2490778 N, 17.3121181 E) is an active and sanitary (with a leachate protective layer) landfill site located in the Zlín Region, the eastern part of the Czech Republic. The landfill activity started in 1995. The landfill is situ-

Fig. 1. Landfill overview

Source: photo by Roman Vlček 2019.

ated in a pronounced morphological depression, and the existing roads III/428 17 Zdounky-Nětčice and III/432 15 Nětčice-Troubky demarcate its premises (Vaverková, Toman & Kotovicová, 2012). Altitudes ranging from 240–396 m a.s.l. indicate the rugged topography. The landfill itself is situated at an altitude of 251–280 m a.s.l. (Fig. 1).

The designed area of the landfill is 70,700 m^2 with a total volume of 907,000 m^3. The planned service life of the facility is up to 2027. The landfill receives waste from a catchment area with a population of around 75,000 residents. The deposited waste is from the communal sphere, non-hazardous waste, including municipal solid waste (MSW). The surrounding area is bordered by agricultural fields. The leachate is collected via a draining system and stored in a leachate pond – a receiving system (Podlasek et al., 2021; Podlasek, Vaverková, Koda, Jakimiuk & Barroso, 2023). The landfill is classified as falling in the S-OO group (other waste), subgroup S-OO3. It is intended for the storage of waste from the category of other waste, including waste materials with a substantial content of organic, biologically decomposable substances, which cannot be assessed based on their aqueous leachates. Hazardous waste is not being deposited in the landfill. Landfill gas is burnt in the motor-generator unit producing electric energy. Part of the landfill body crown is operated as a composting plant. There is a recycling area on the part of the landfill site on which inert demolition waste material is processed and stored (Vaverková et al., 2012; 2019; 2020; 2022).

Natural conditions

The area on which the landfill is situated was formerly used for agriculture – mainly plant production (Fig. 2). The terrain is formed by a wide valley with an elevation of up to 30 m, and the valley bottom descends in an approximately westerly direction. The area's hydrographic axis is the surface watercourse of Lipinka, which opens into the Olšinka on the western limit of Zdounky. After approximately 500 m, the Olšinka opens in the Kotojedka surface stream. All these watercourses are of little importance for water management in the area.

Climatically, the area belongs in the T2 warm zone with warm to mildly warm springs, long warm and dry summers, very short transitional periods of autumn, and mildly warm, dry to very dry winters with a very short period of snow cover (Vaverková et al., 2012; 2019).

Technical description of the landfill

The landfill site is fenced and located on an area of 18.4 ha. The body of the landfill in Stage I occupies 1.92 ha, Stage IIa 0.55 ha, Stage IIb 0.47 ha, Stage III 0.75 ha, Stage IIIb 0.71 ha, Stage IV 0.58 ha, Stage V 0.69 ha, and Stage VI 0.61 ha.

Fig. 2. Landfill body and landfill surrounding

Source: photo by Roman Vlček 2019.

The entire complex consists of the following: (i) operational building; (ii) landfill body; (iii) leachate pond; (iv) surface water; (v) final embankment; (vi) catchment ditches; (vii) weighbridge; (viii) monitoring system; (ix) composting facility; (x) landfill degasification.

The operational building (i) is situated to the left of the service road before arriving at the landfill itself. It is a one-story building without a basement. There are employee changing rooms, sanitary facilities, a kitchen, a warehouse, an office and a weight room. During Stages I and II, a 5 × 200 mm mineral seal ($kf = n \cdot 10^{-10}$ m·s^{-1}), a 2 mm thick insulating film and a non-woven geotextile were placed on the compacted plain of the landfill body (ii). The entire system was completed with a 300 mm thick surface drainage made of river gravel (fraction 16–32 mm) at a 5% slope to the central leachate collector – the downspout. During Stage IIb, a 2 × 250 mm mineral seal, a 2 mm thick polyethylene high-density (PEHD) film and a non-woven geotextile were placed on the compacted plain. The system is complemented by surface drainage from the sorted river gravel (fraction 16–32) with a thickness of 300 mm. During Stage III, a 2 × 250 mm mineral seal, a 1.5 mm thick PEHD film and a non-woven geotextile were placed on the compacted plain. The system is complemented by a 500 mm thick surface drainage made of river gravel (fraction 16–32 mm). During Stage IIIb bentonite mats, a 2 mm thick PEHD film and a geotextile were placed on the compacted plain. The system was supplemented with surface drainage with a thickness of 500 mm from river gravel (fraction 16–32 mm). During Stage IV, bentonite mats, a 2 mm thick PEHD film and a geotextile were placed on the compacted plain. The system is completed with used tyres and surface drainage with a thickness of 300 mm from gravel (fraction 16–32 mm). During Stage V, bentonite mats, a PEHD film with a thickness of 2 mm and a non-woven geotextile (1,200 g·m^{-2}) were placed on the compacted plain. The system is completed with used tyres and surface drainage with a thickness of 300 mm from natural quarried aggregate. During Stage VI, bentonite mats, a PEHD film with a thickness of 2 mm and a non-woven geotextile were placed on the compacted plain. Used tyres are placed on it and covered with surface drainage (natural mined aggregate) 300 mm thick (DEPOZ, 2018). The leachate pond (iii) is a drainless and reinforced concrete structure. It consists of three tanks, of which the middle one (the so-called dry one) is covered and houses the pipelines, valves, and a pump for reverse discharge. Both open tanks are equipped with an insulating PEHD foil. The total size of the pit is 41 × 11 m. The surface water (iv) well consists of two open, interconnected reinforced concrete tanks with a total dimension of 38 × 16 m. The landfill body itself is supported on the slopes of the terrain depression and on the south side in an earthen embankment (v) designed to meet the requirements of static and deformational stability. Catchment ditches (vi) are around the perimeter of the entire landfill that collect runoff from the catchment area and the area above the landfill. Other branches are led along the perimeter of Stages I, II, IIIb, IV and VI, and capture the inflow to these stages. The branch above the technical background prevents the possible inflow of water onto the paved surfaces. All ditch profiles are trapezoidal and equipped with grooves. The weighbridge (vii) is located in the area in front of the operational building. The entire weighing system is stored below ground level in a reinforced concrete sump, forming the basis of the scale. The monitoring system (viii) is implemented by four monitoring wells: MV1 – depth 15 m, MVb – depth 11 m, MV4 – depth 15 m, MV5 – depth 15 m and well MV6 – depth 10 m. The composting facility (ix) is located within the body of the landfill. Landfilling was completed at the site. The area was covered with recycled material and compacted with a vibrating roller. Landfill degasification (x) using 12 vertical gas wells have been installed in the Stage I area, 3 wells in the Stage IIa area, 4 wells in Stage IIIa, 2 wells in Stage IIb, 5 wells in Stage IIIb, 3 wells in Stage IV, 4 wells in Stage V and 4 wells in Stage VI. Landfill gas is transported via a collection and conveyance system through a condensing and control shaft to the cogeneration unit. Here, electricity is generated and supplied to the public grid. The individual gas wells are gradually connected to the collection system depending on the quality and quantity of the gas and in connection with the closure of the landfill on the individual cassettes. Some of the wells where the gas permeability has been reduced due to casing movement are plugged, and new wells drilled in their vicinity. The cogeneration unit consists of two separate containers (3 × 5 m) fitted with a pump, an internal combustion engine and a control unit. The installed capacity is 2 × 160 kW (DEPOZ, 2018).

Vegetation monitoring at the landfill

Vegetation monitoring took place in the Zdounky locality at the MSW landfill, at two locations. The first site was a landfill with active waste disposal (Fig. 3), and the second was a reclaimed part of the landfill (Fig. 4).

Vegetation was evaluated using a floristic inventory of the species found. Vegetation was determined in the selected area of the MSW landfill. The identified plant species were recorded. Biological monitoring was carried out in July 2019. The scientific names of individual plant species were used according to Danihelka, Chytrý, Kučera and Palice (2017). The occurrence of each species found was evaluated on a simple three-point scale.

Scale evaluating the intensity of species occurrence: 3 – very abundant species with dominant

Fig. 3. The active part of the landfill with a composting plant

Source: photo by Magdalena D. Vaverková 2022.

Fig. 4. The reclaimed part of the landfill

Source: photo by Magdalena D. Vaverková 2022.

occurrence (dominant species); 2 – a common species with an abundant occurrence only in some parts of the landfill (subdominant species); 1 – a rare species with a small and rare occurrence.

Each plant species was classified according to the method of pollen transfer, the evaluation of the pollen as an allergen, and according to the method of dispersal of fruits and seeds. This information was taken from the database of Czech flora and vegetation, Pladias (Pladias, 2014–2023). The plant species producing allergenic pollen were taken from the database of the Czech Pollen Information Service (*Česká pylová informační služba* – PIS), which was founded in 1992 in Brno and monitors the occurrence of pollen and other biological objects in the air. The processed data serves doctors and patients to improve the quality of treatment. The PIS monitors the situation of 11 monitoring stations (Česká pylová informační služba [PIS], 2022).

According to the method of pollen transfer, the species were divided into: H – insect-borne (animal transmission); V – wind-borne (wind-borne); A – autogamy (self-fertilisation).

According to pollen as an allergen, the species were divided into three categories: 3 – species producing allergenic pollen that is monitored by PIS; 2 – wind-borne species, in which pollen is spread by the wind, but does not belong to strong allergens; 1 – insect-pollinating species, in which pollen is transmitted by insects and only gets into the air to a limited extent.

According to the method of transmission of fruits and seeds, the species were divided into: H – zoochoric (animal transmission); V – anemochoric (wind transmission); S – other mechanisms.

RESULTS AND DISCUSSION

Possible environmental impacts of the landfill

Impact on air and climate. The MSW Zdounky landfill is classified as a stationary source with respect to Czech Act No 201/2012 Coll. on air protection (Zákon ze dne 2. května 2012 o ochraně ovzduší). In accordance with this Act, the operating rules are laid down, and the landfill is operated in accordance with them. The operating rules include steps to minimise dust and odours (DEPOZ, 2018). These include primarily depositing waste in layers and continuous compaction with a compactor, then covering it with an inert material to prevent light particles from drifting and the release of particulate matter. Overlaying with inert material is also of hygienic importance. In addition, catch nets are installed, and greenery planted around the perimeter of the landfill to prevent materials from escaping from the landfill site. These measures are monitored daily. Emissions from transport and handling equipment at the landfill are not significant (portal.cenia.cz). Municipal solid waste landfill produces landfill gas (Adamcová, 2019; Purmessur & Surroop, 2019; Vaverková, 2019; Anshassi, Smallwood & Townsend, 2022), which is composed of gases (CH_4, CO_2, O_2, H_2S and others). The most important is CH_4, in terms of calorific value and, therefore, recoverability (Vaverková, 2019; Lee, Kim, Kim, Kwak & Kim, 2020). Methane is also a major greenhouse gas (Allen et al., 2020; Chetri, Reddy & Grubb, 2022). At the MSW Zdounky landfill, a landfill gas collection system is created and then burned in a cogeneration unit to produce electricity. In case of failure of the cogeneration unit or for other reasons, the degasification system is equipped with a flare to burn the gas so that it does not enter the air. As the landfill body expands, the degasification system is gradually enlarged (DEPOZ, 2018).

The effect of noise. Noise in the landfill area is mainly caused by the transport of waste and the place of its permanent storage and the subsequent handling of waste, including, for example, spreading and compaction (Vaverková, 2019; Hoang, Pham, Mai, Nguyen & Tran, 2022). A dense belt of greenery around the perimeter of the landfill helps to prevent the transmission of noise from the body of the landfill. It also helps the distribution of the terrain, namely, the mechanisation mostly moves below the level of the surrounding terrain. Noise does not spread outside the landfill, and the landfill area is located outside the built-up area (portal.cenia.cz).

Impact on water resources. Water quality is a good indicator of the spread of potential pollution from a landfill (Guo, Li, He & Wang, 2022; Podlasek et al., 2023). At the same time, water is also a good spreader of these pollutions (Pan, Ng & Richter, 2019). It is formed by biological decomposition, underground water inflows and rainfall (Vaverková, 2019; Koda et al., 2022; Podlasek et al., 2023). Water monitoring is carried out twice a year at the MSW Zdounky landfill. In addition to quality, other indicators of underground and leachate are monitored in four monitoring wells (MV1, MV2b, MV4 and MV5), (portal.cenia.cz). Long-term groundwater monitoring shows that the water quality in the area below the landfill is slightly worse than in the area below the landfill (Podlasek et al., 2023). The increased concentration of some substances, caused, for example, by agriculture, will manifest itself in the area under the landfill after at least a year, sometimes even longer. The landfill drainage system solution is designed to separate landfill and other waters from each other. Landfill waters are all waters that have come into contact with waste or could potentially come into contact with and are, therefore, contaminated leachates from waste. Thanks to the observance of the given procedures, the potential risk of leakage of landfill water is minimised. Leachate is collected and then transported to the wastewater treatment plant (DEPOZ, 2018).

Impact on soil. The agent that could cause soil contamination is water. To prevent the bedrock from coming into contact with landfill water, which is a potential spreader of contamination, the body of the landfill is secured with a two-layer waterproofing. Water that has come into contact with waste is channelled into a leachate pond using a drainage system so that it does not come into contact with rainwater (Vaverková, 2019). There was no evidence of any influence on the surrounding agricultural land by the landfill operation (Vaverková et al., 2019; 2020; Podlasek et al., 2021).

Results of vegetation surveys on the landfill under investigation

From the floristic inventory of plants at the Zdounky landfill, the most important plant species were selected and ranked according to their intensity of occurrence and allergen strength (Tables 1 and 2).

From Tables 1 and 2, it is clear that the Zdounky landfill, both in the reclaimed and active parts, contains a wide variety of abundant vegetation. Some significant allergenic plants were found, identical to the biomonitoring of Vaverková et al. (2019). These plants include: *Atriplex sagittata*, *Amaranthus retroflexus*, *Artemisia vulgaris*, *Bromus sterilis*, *Echinochloa crus-galli* and *Elytrigia repens*.

Since pollen can spread even several kilometres away, a waste landfill that has been recultivated with grass, from an anthropocentric point of view, represents a potential risk of developing allergies in the vicinity of the landfill. According to Vaverková et al. (2019), reforestation reduces the proportion of allergens in the

Table 1. List of selected plant species from the reclaimed part of the landfill

Plant	Intensity of occurrence	Pollination vector	Allergies	Propagation of fruit and seeds
Arrhenatherum elatius	3	A, V	3	S, V
Calamagrostis epigejos	3	V	3	V
×Festulolium	3	V	3	S, V
Artemisia vulgaris	2	V	3	V
Dactylis glomerata	2	A, V	3	S, V
Elytrigia repens	2	V	3	S
Festuca pratensis	2	V	3	S, V
Festuca rubra	2	V	3	S, V
Lolium perenne	2	V	3	S, V
Phleum pratense	2	A, H, V	3	S, V
Phragmites australis	2	V	3	S, V
Plantago lanceolata	2	H, V	3	S
Poa pratensis	2	A, V	3	S, V

H – insect-borne (animal transmission), V – wind-borne (wind-borne), A – autogamy (self-fertilization), S – other mechanisms.

Source: own work.

Table 2. List of selected plant species from the active part of the landfill

Plant	Intensity of occurrence	Pollination vector	Allergies	Propagation of fruit and seeds
Atriplex sagittata	3	V	3	S
Amaranthus powellii	2	V	3	S
Amaranthus retroflexus	2	V	3	S
Artemisia vulgaris	2	V	3	V
Bromus sterilis	2	A	3	S, V
Calamagrostis epigejos	2	V	3	V
Echinochloa crus-galli	2	V	3	S, V
Elytrigia repens	2	V	3	S
Chenopodium album	2	V	3	S, V
Robinia pseudoacacia	2	H	3	S
Rumex obtusifolius	2	V	3	V
Sambucus nigra	2	H	3	S, H
Urtica dioica	2	H, V	3	S, V
Tripleurospermum inodorum	2	H, V	2	S

H – insect-borne (animal transmission), V – wind-borne (wind-borne), A – autogamy (self-fertilisation), S – other mechanisms.

Source: own work.

air and, at the same time, contributes to the improvement of air quality. Due to the fact that the reclamation of the landfill by planting grass poses a potential threat in the presence of various allergenic pollens, reclamation by afforestation is recommended, if possible (Vaverková et al., 2022). Nevertheless, grasses are of great importance in terms of nutrient exchange in the soil and water infiltration. An advantage is the speed of growth, the ability to survive on waste material (Winkler et al., 2021), and resistance to adverse pH and toxic metals. Their abundant root system prevents soil erosion. Therefore, if the situation requires recultivation of the landfill by grassing, it is recommended to use plant species of the *Fabaceae* family in the seeding mixture, because during growth, grasses are demanding on nitrogen, and this family is able to supply atmospheric nitrogen to the cycle. At the same time, they are among the entomophilous species, which means that their pollen only enters the air in limited quantities, and therefore they are not among the significant producers of allergenic pollen. Examples of such species can be *Medicago lupulina* and *Lotus corniculatus*.

The propagation of fruits and seeds of plants is of great importance from the point of view of succession. During succession, there is an alternation of individual plant species with different life strategies and properties. The course of succession is influenced by a number of circumstances, for example, the surrounding seed source, meteorological conditions, soil composition, etc. (Winkler et al., 2021; Koda et al., 2022). The vast majority of vegetation found at a waste landfill is the type commonly found in human-impacted environments (Winkler et al., 2021; Vaverková et al., 2022). However, the existence of this vegetation is of great importance – especially ecologically – due to the creation of conditions for the next stage of succession. In the vicinity of the Zdounky landfill, there is predominantly agricultural land. The floristic surveys confirmed that the area of the landfill has a higher species diversity than the surrounding landscape. This was confirmed by Vaverková et al. (2019; 2020; 2022).

However, there is also a potential risk of the positive effect of the landfill on the species diversity of the landscape (Vaverková et al., 2019; 2020; 2022; Winkler et al., 2021). Several invasive and non-native plant species were found in the active part of the Zdounky landfill. Specifically: *Acer negundo*, *Arrhenatherum elatius*, *Conyza canadensis* and *Reynoutria japonica*.

Their potential risk lies in endangering the preservation of biological diversity, both at the species level (danger of crossbreeding and loss of genetic variability and competition) and at the community level. If a non-native species has abilities that can give it an advantage over native species, it starts to expand intensively (invasive species). These are plant species that spread with the help of the wind, and there is a great potential risk of spreading to the surroundings of the landfill (Winkler et al., 2021).

During the floristic survey by Vaverková et al. (2012) several species were found on the reclaimed part of the landfill: (i) *Plantago major* – the soil eutrophication indicator indicates an increased concentration of inorganic nutrients in the soil (mainly nitrogen and phosphorus). These conditions in the soil can also be influenced by the fact that the land around the landfill is intensively used for agriculture. These inorganic substances can also affect the reclaimed part of the landfill; (ii) *Symphytum officinale* and *Urtica dioica* – are indicators of elevated or high nitrogen in the soil; (iii) *Silene vulgaris* – indicates an increased or high occurrence of heavy metals in the soil. The types of waste deposited at the landfill can play a role here, potentially affecting the soil in the reclaimed part of the landfill.

CONCLUSIONS

Waste landfills already have an impact on the environment during construction, mainly due to noise and dust caused by increased traffic and mechanisation in the vicinity of the landfill. During the operation of the landfill, there is a risk of landfill gas and leachate generation, dust and fine particles floating from the body of the landfill, noise, etc. After the completion of exploitation and reclamation of the landfill, efforts are made to integrate it into the landscape in the most appropriate way and to minimise the impact on the surrounding ecosystems. In this context, choosing the right reclamation method is very important. Despite the fact that landfilling of waste is abandoned, this does not mean that this potential risk and impact on the surrounding landscape that landfills represent will disappear. Reclaimed landfills still need to be monitored. In addition to continuous monitoring of leachate and gas, biomonitoring using plant bioindicators can also serve this purpose. Thanks to appropriately selected bioindicators, the impact of the landfill load on the surrounding landscape can be determined.

During the landfill biomonitoring, no significant impacts of the landfill on the surrounding environment were detected. The plant species found were recorded and evaluated based on the frequency of occurrence, pollination vector, distribution of fruits and seeds, and intensity of allergen effects. However, thanks to the occurrence of 23 strong plant allergens at the landfill, there is a potential risk of the spread of allergens to the surroundings of the landfill, which appears to be a risk for humans. Furthermore, some species of non-native and invasive plants were found on the active part of the landfill, which were most likely brought to the landfill together with the waste. These species spread their seeds and fruits with the help of the wind; therefore, they pose a potential risk to the surrounding ecosystems. It is evident that the landfill can become a source of weeds in agricultural land and other areas.

Despite this, several new species of plants were also found at the monitored landfill, which highlights the ongoing succession at the landfill. In some circumstances, landfills can be considered a favourable environment for the development of a range of plants and a refuge for animals. These results show that the landfill can, on the contrary, have a positive effect on the surrounding landscape, as it exhibits a higher degree of biodiversity than the surrounding intensively agriculturally-used landscape. Although landfilling is last in the hierarchy of waste management and, therefore, the least suitable way to manage waste, it can be of some benefit to the landscape if it is operated in accordance with regulations and properly monitored. In this case, it does not pose a significant threat to the surroundings, and on the contrary, it can be integrated into the surrounding landscape and become part of the surrounding ecosystems.

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OCENA ODDZIAŁYWANIA WYBRANEGO SKŁADOWISKA ODPADÓW NA ŚRODOWISKO – STUDIUM PRZYPADKU

STRESZCZENIE

Składowanie jest najstarszą metodą unieszkodliwiania odpadów. Na składowiskach zachodzi wiele reakcji biologicznych, chemicznych i fizycznych, które powodują zagrożenie dla środowiska. Z tego powodu monitoring składowisk jest niezbędny, a biomonitoring zaczyna być coraz częściej wykorzystywany. Niniejszy artykuł ma na celu: (a) określenie niektórych oddziaływań składowiska odpadów na otaczające środowisko, (b) analizę bioindykatorów roślinnych oraz (c) biomonitoring na podstawie występowania gatunków roślin produkujących alergogenny pyłek. Ponadto analizie poddano występowanie roślin produkujących owoce i nasiona. Podczas badań nie wykryto poważnego oddziaływania składowiska na otaczające środowisko. Stwierdzone gatunki roślin oceniono na podstawie częstości występowania, wektora zapylania, rozmieszczenia owoców i nasion oraz intensywności działania alergenu. Ze względu na występowanie roślinnych alergenów istnieje potencjalne ryzyko ich rozprzestrzeniania się w otoczeniu składowiska. Ponadto na eksploatowanej części składowiska stwierdzono obecność niektórych gatunków roślin nierodzimych i inwazyjnych. Gatunki te rozprzestrzeniają nasiona i owoce, więc stanowią potencjalne zagrożenie dla ekosystemów.

Słowa kluczowe: stałe odpady komunalne, oddziaływanie składowisk, biomonitoring

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DURABILITY TESTS OF GEOSYNTHETIC MATERIALS USED IN DIFFICULT ENVIRONMENTAL CONDITIONS

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ABSTRACT

The article describes the ageing process of high-density polyethylene (HDPE) geogrids under the influence of chemical and environmental factors. Research on accelerated ageing of a uniaxial HDPE geogrid incubated in a water solution for a period of 12 months is presented. Three temperatures (25°, 45° and 75°C) were selected for the accelerated ageing tests in aqueous solutions simulating the conditions at a municipal waste landfill. Changes were observed using differential scanning calorimetry (DSC), and correlations with the mechanical properties of the aged geogrid were checked. No significant effect of the loss of antioxidant in the material on the mechanical properties of the uniaxial geogrid was observed. The tests made it possible to determine the mechanical properties, such as tensile strength and deformability of the geogrid – which are extremely important in the analysis of slope stability.

Keywords: accelerated ageing tests, oxidative degradation, strength of polymeric materials, HDPE geogrids

INTRODUCTION

Geosynthetic materials used in engineering structures must be characterised by a specific strength and durability over time. The durability of geosynthetics depends on (Greenwood Schroeder & Voskamp, 2012):

- the type of raw material used, from which material it was made, and the additives used in the production (i.e., antioxidants, stabilisers, fillers, plasticisers);
- resistance to chemical and microbiological influences;
- resistance to mechanical damage caused during storage, installation and operation during the designed period of use.

The mechanism of the oxidative degradation process for polyolefins, consist of three stages: initiation, propagation and termination (Hsuan et al., 2008).

The factors initiating polymer degradation may be the following interactions: physical (e.g., temperature, constant and cyclic loads, UV radiation), chemical (e.g., oxygen, solutions, pH, heavy metals) and biological under the influence of living organisms (e.g., bacteria, fungi – these are organisms commonly found in soil, groundwater, landfills). The actions of degrading factors in the environment are often synergistic, and their effect is interactions between individual stimuli. During degradation in natural climatic conditions, it is very difficult to isolate which degrading factors have a dominant effect on a given synthetic material (Rabek, 2013; Valentin et al., 2021). Polyolefin materials have a semi-crystalline, crystalline and amorphous structure, which means they can undergo oxidative degradation at different rates. The oxidation reaction takes place both in the bulk and on the surface of the polymer depending on the amount of oxygen

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and temperature. The effects of chemical degradation are accelerated by the influence of elevated temperature (Ehrenstein, Riedel & Trawiel, 2004).

Geosynthetic materials are usually made of thermoplastic polymers. In their structure, they contain amorphous domains, where the polymer chains are arranged randomly, and crystalline domains, where the polymer chains are arranged regularly – most often in the form of crystalline lamellae (Fig. 1).

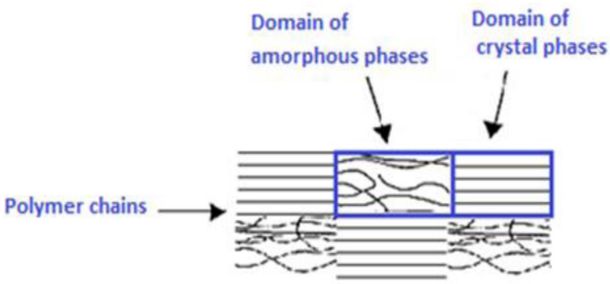

Fig. 1. The structure of thermoplastic polymers

Source: Hawkins (1972).

The durability of polymers used in the production of geosynthetic materials also depends on stabilising additives, thanks to which their degradation can be significantly delayed. The use of stabilising agents, the geosynthetic lifetime is extended 10 or even 100 times, depending on the environment in which it was used (Greenwood et al., 2012; Scholz et al., 2021). Additives, due to their functions in the plastic, can be divided into:

– processing additives (processing stabilisers, processing modifiers);
– functional additives (property stabilisers, property modifiers).

Processing additives affect the course of processing processes, while in the form of functional additives, they affect the usable properties of the material. In addition, in both cases, these agents can be used to stabilise and modify the processing or use properties of polymers.

These include fillers, stabilisers (e.g., antioxidants), softeners (plasticisers), light stabilisers, colouring agents, antistatics and flame retardants (Zweifel, 2000; Bart, 2005). Various types of additives used in the production of geosynthetics are intended to support the manufacturing processes and protect them over time. Polyethylene oxidation reactions can be delayed or inhibited by the use of primary (hindered phenols and sterically hindered amines) and secondary (trisubstituted phosphates or sulphoxides) anti-oxidants that capture free radicals by decomposing hydroperoxides to alcohol and this process prevents further propagation of the chain (Fay & King, 2013). Under certain conditions, additives can be partially or entirely depleted from the material, such as washed out by water or chemicals (e.g., solvents, surfactants) from the surface of the material. As a result of the oxidation of the polymer, the resulting free radicals lead to chain reactions (auto-oxidation). The formation of free radicals causes the breaking of polymer chains, which leads to a decrease in the molecular weight of the polymer. The result of this phenomenon is that the material consequently becomes brittle and at the same time susceptible to stress corrosion cracking (Elias, Kenneth, Fishman, Christopher & Berg, 2009). Under the influence of atmospheric oxygen, the oxidation process occurs with the formation of polar groups such as hydroxyl (-OH), carboxylic (-COOH), hydroperoxide (-OOH) and ketone (>C=O).

The influence of temperature (or radiation) can be catalysed by transition metal ions or catalyst residues from the polymerisation process. It should be emphasised, however, that these processes depend on the availability of oxygen present in the polymer. Moreover, the speed of the initiation process depends on the temperature and concentration of macroradicals.

When using polyolefin geosynthetics, the main problem is assessing their durability under various ageing conditions. The antioxidants used protect the material against its oxidative degradation, but are gradually depleted over time. Oxidative degradation of HDPE geosynthetics can be divided into three distinct stages (Fig. 2):

– Stage I – the time of depletion of antioxidants, is caused by their consumption as a result of chemical reactions (reaction of free radicals with oxygen) or physical losses due to diffusion, extraction or evaporation.
– Stage II – induction time needed for the occurrence of oxidative degradation of the polymer after complete depletion of the antioxidant.

– Stage III – the proper degradation of the polymer leading to the deterioration of its measured properties, primarily mechanical parameters (the polymer becomes brittle). The action of mechanical loads can also destroy molecular chains and enhance the effects of elevated temperature and oxygen (Hsuan & Koerner, 1998).

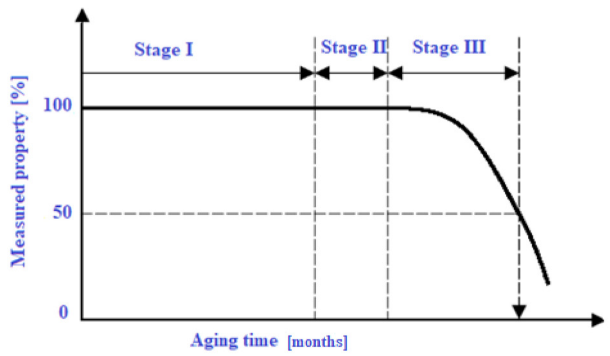

Fig. 2. Three stages of oxidative degradation: Stage I – antioxidation depletion; Stage II – Induction time; Stage III – the half-life of property

Source: Hsuan and Koerner (1998).

This article focuses on determining the durability of uniaxial HDPE geogrid used to strengthen slopes and embankments. The tests of the accelerated ageing process were carried out in a solution simulating the conditions prevailing in a municipal waste landfill for a period of 12 months. Three temperatures (25°C, 45°C and 75°C) were selected for this study. The heavy metals used in the effluents acted as a catalyst for hydroperoxide decomposition to generate free radicals and deplete antioxidants in the plastic. The surfactants used in the effluent increased the wetting capacity of the geosynthetics.

The presented results indicate that uniaxial polyolefin geogrids can be used for soil reinforcement in geotechnical structures, even in places where the influence of chemical factors and elevated temperature is significant.

MATERIAL AND METHODS

The HDPE geogrids were used for laboratory tests. Geogrids belong to the group of related materials (GTP) according to the classification of the PN-EN ISO 10318-1 standard (Polski Komitet Normalizacyjny [PKN], 2018a). They are used where there is a need to increase the shear strength of the soil for structures: slopes, road and railway embankments, and platforms as well as when the structure is founded on a weak foundation (Wesołowski, Krzywosz & Brandyk, 2000). The structure of uniaxial geogrid (with rigid nodes) is obtained by extrusion from the sheet and then stretching at a properly selected temperature, depending on the raw material used, to give the geosynthetic material the appropriate shape and strength characteristics. Table 1 shows the main engineering properties of the uniaxial HDPE geogrid.

Table 1. The main engineering properties of the uniaxial HDPE geogrids

Parameter	Value
Geometry	
Aperature size [mm]	16 × 235
Rib thickness [mm]	1.1
Cross machine direction (CMD) bar thickness [mm]	2.5–2.6
Rib width [mm]	6
Weight [g·m^{-2}]	500
Mechanical properties	
Tensile strength [kN·m^{-1}]	60.5
Elongation at rupture [%]	12.2
Resin properties	
Melt flow index [g·10 min^{-1}]	0.07
Oxidation induction time [min]	65

Source: Kiersnowska (2017).

The accelerated ageing tests were conducted according to similar studies reported in the literature (Rowe, Islam & Hsuan, 2008) and with the conditions prevailing during the exploitation of geogrids (backfilling with anthropogenic soil). The temperature and composition of the water environment were selected as factors causing degradation, as described in Table 2, the surfactant Triton™ X-100 (Sigma-Aldrich, Germany) at a concentration of 5 ml·l^{-1} was used. Three ageing temperatures of the samples were determined: 25 ±2°C, 45 ±2°C and 75 ±2°C. After analysing the annual reports from the Radiowo landfill No 19932018 (Golimowski & Koda, 1993–2018), the pH of the incubation solution was set at 6. The ageing period of the geogrid samples was planned for 12 months. Test samples were taken from the solutions every 2 months. In order to maintain the continuity of antioxidant depletion from the geogrid, the solution was replaced every 2 months. Geogrid samples (520 × 240 mm) were placed in glass tubes in a 50-litre stainless steel container, poured with a previously prepared solution, heated to a specific temperature and pH adjusted.

Table 2. The composition of the heavy metal solution

Component	Concentration [$mg \cdot l^{-1}$]
Ferrous sulphate ($FeSO_4 \cdot 7H_2O$)	4 480
Zinc sulphate heptahydrate ($ZnSO_4 \cdot 7H_2O$)	360
Cupric sulphate pentahydrate ($CuSO_4 \cdot 5H_2O$)	40
Aluminium sulphate 16-hydrate ($Al_2(SO_4)_3 \cdot 16H_2O$)	30
Manganous sulphate 4-hydrate ($MnSO_4 \cdot 4H_2O$)	60
Nickel(II) sulphate ($NiSO_4 \cdot 6H_2O$)	50

Source: Kiersnowska, Fabianowski and Koda (2020).

In order to perform oxidation induction time tests, geogrid samples were taken from the place where the geogrid ribs had the smallest thickness and width. With these parameters the material after incorporation in this place is most exposed to the influence of the surrounding environment. A thermal analysis apparatus DSC Q200 (TA Instruments, USA) was used for the test (Fig. 3). The test was performed in accordance with the PN-EN ISO 11357-6 standard (PKN, 2018b). An open sample pan and a reference pan (empty aluminium pan) were placed in the measuring cell. The measurement was carried out in a nitrogen atmosphere (with a gas flow of 50 $ml \cdot min^{-1}$ ±5 ml) at a heating rate of 10°$C \cdot min^{-1}$ to the measurement temperature of 200°C. After reaching the assumed temperature, the inert gas (nitrogen) was switched to oxygen and the measurement was continued in isothermal conditions at the heating rate (5°$C \cdot min^{-1}$).

Oxidation induction time (*OIT*) was determined by the intersection of the tangents to the baseline and the rectilinear segment observed while measuring the oxidation signal (oxidation isotherm). Then, the value at

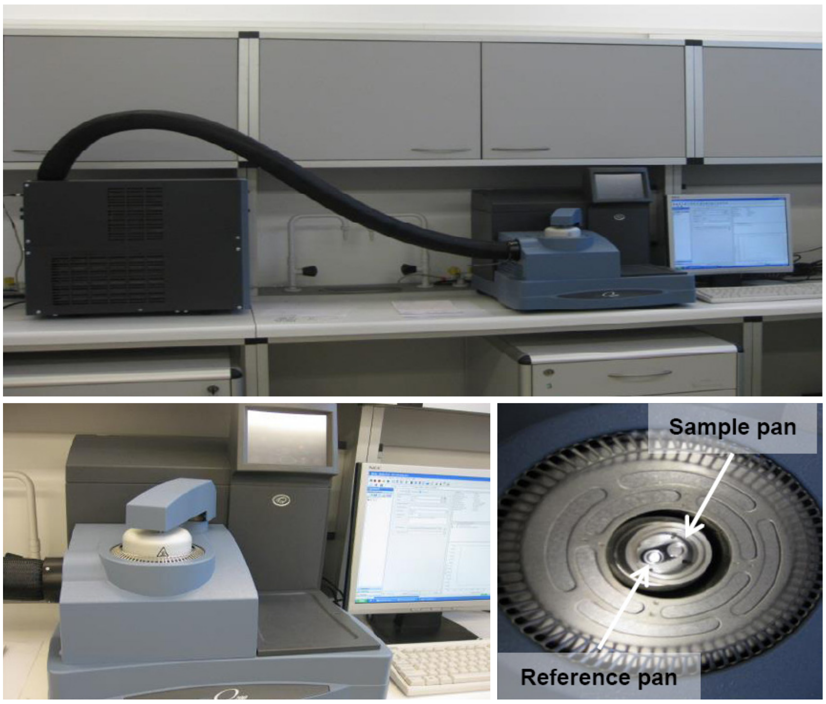

Fig. 3. Differential Scanning Calorimeter Q200 oxidation induction time apparatus

Source: own work.

which the inert gas atmosphere was changed to oxygen was subtracted from the time value for the obtained point (approx. 20 min). Determination of the intersection of the tangents to the baseline and the rectilinear segment observed during the measurement of the oxidation signal (oxidation isotherm) allowed to designate *OIT*. Then, from the time value for the obtained point, the value at which the inert gas atmosphere was changed to oxygen (approx. 20 min) was subtracted (Fig. 4). Each test was conducted in duplicate.

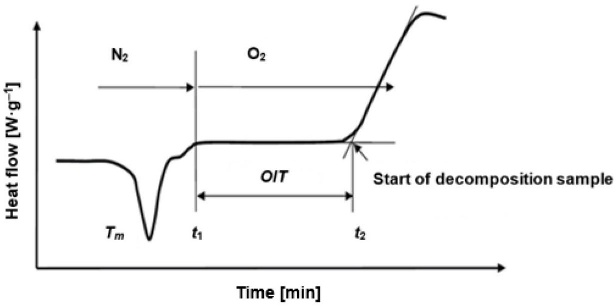

Fig. 4. Schematic diagram of analysis by differential scanning calorimeter of standard oxidation induction time (*OIT*): T_m – melting temperature of polymer; t_1 – the beginning of the oxidation; t_2 – the end of the oxidation

Source: PKN (2018b).

When the geosynthetics function as reinforcement for their tensile strength, the elongation at maximum load are crucial for assessing product stability since the action of elevated or reduced temperature and humidity changes their properties. The tests for new and aged geogrid were carried out in accordance with the PN-EN ISO 10319:2015-08 standard (PKN, 2016) using a tensile testing machine (Instron, USA) with a maximum force of 100 kN. For each test five specimens were used. The monotonic tensile tests were performed at a rate of strain equal to 20% min^{-1}. For each test, five specimens were used.

RESULTS AND DISCUSSION

Figure 5 shows that the antioxidant from the geogrid subjected to accelerated ageing tests at 75°C depleted the fastest. Oxidation induction time (*OIT*) tests for the sample after 8 months of ageing (75°C) showed no antioxidant, so the first stage of geogrid degradation was completed. For the sample aged for 12 months at 25°C, the antioxidant content remained at 60%. For the sample aged for 12 months at 45°C, 38% of the reference sample remained.

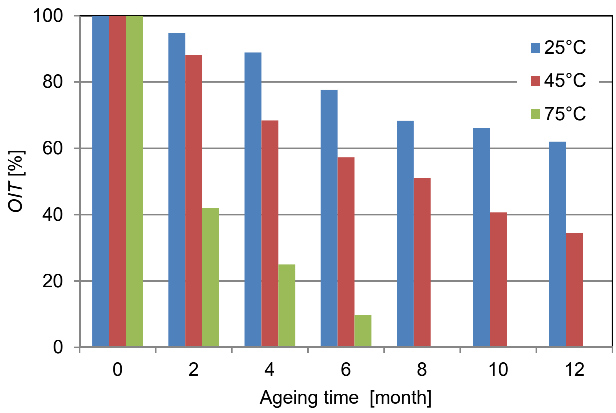

Fig. 5. Oxidation induction time (*OIT*) for samples subjected to accelerated ageing tests for 12 months at three selected temperatures

Source: Kiersnowska, Fabianowski, Koda, Trach and Kawalec (2022).

Table 3 shows the relationship between the average tensile strength (*F*) and the ageing time of geogrid samples. The average tensile strength of geogrid samples not subjected to ageing tests was 60.56 kN·m^{-1}. The average tensile strength values for samples incubated at 25°C ranged from 61.00 kN·m^{-1} (after 4 months of incubation) to 61.35 kN·m^{-1} (after 12 months of incubation). On the other hand, the average tensile strength values of the samples incubated at 45°C ranged from 62.20 kN·m^{-1} (after 4 months of incubation) to 61.55 kN·m^{-1} (after 12 months of incubation). For samples incubated at 75°C, mean *F* values ranged from 61.06 kN·m^{-1} (after 2 months of incubation) to 62.75 kN·m^{-1} (after 12 months of incubation). After 12 months of accelerated ageing tests at individual temperatures, there were no statistically significant changes affecting the average tensile strength in wide sample tests.

No significant changes in the influence of accelerated ageing tests on the average relative elongation at 25°C and 45°C of the tested material were observed. Accelerated ageing tests at 75°C showed that the

Table 3. Influence of incubation time on tensile strength (F) and elongation at maximum force (F) at selected temperatures for unidirectional HDPE geogrid samples

<table>
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[°C]</th><th>Tensile strength (F)
[kN·m^{-1}]</th><th>Elongation (ε) at maximum strength (F)
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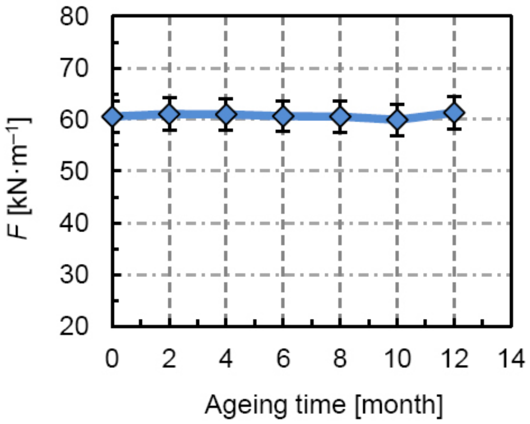
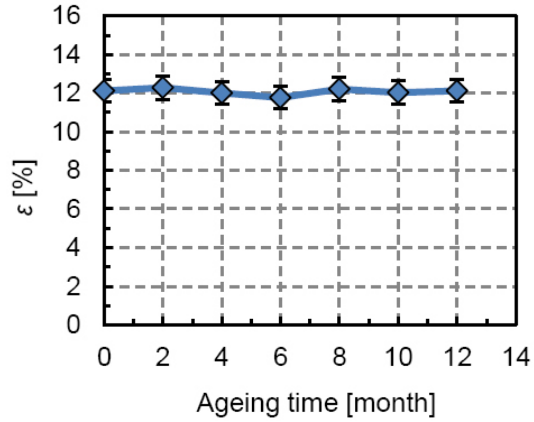
<tr><td>25</td><td>
</td><td>
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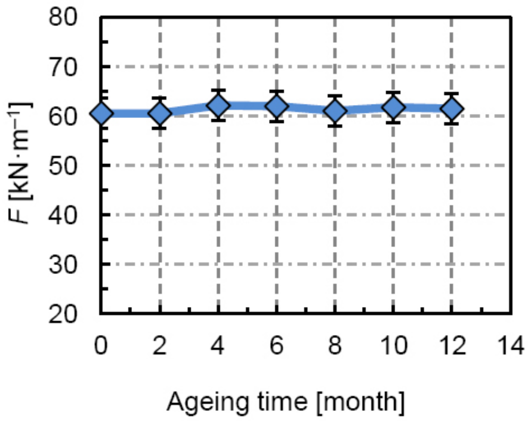
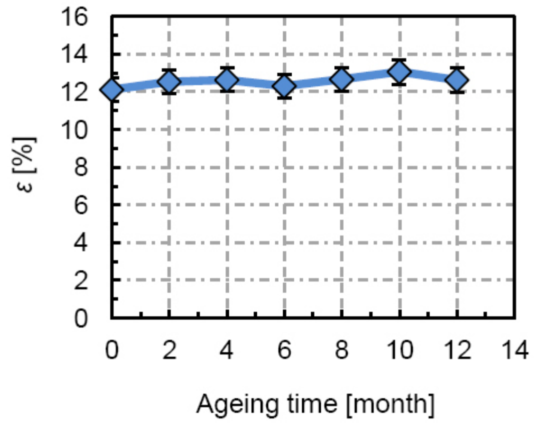
<tr><td>45</td><td>
</td><td>
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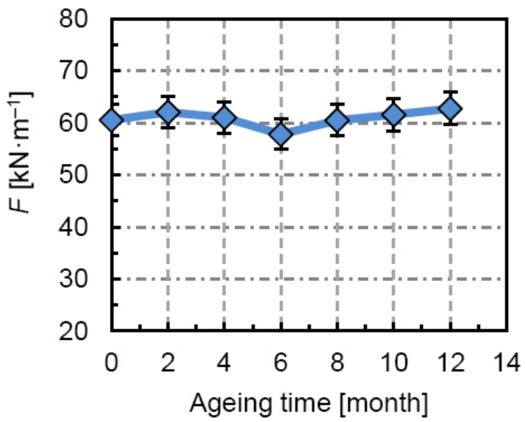
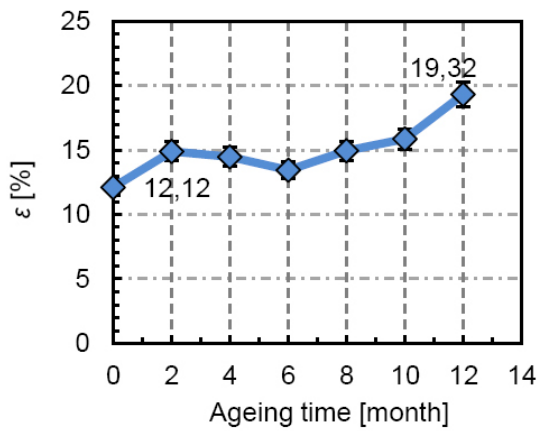
<tr><td>75</td><td>
</td><td>
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Source: Kiersnowska et al. (2022).

average elongation of 12.12% for the sample not subjected to accelerated ageing tests (the new sample) increased to 19.32% (after 12 months of incubation). This study indicates that high-temperature incubation was not indicated for unidirectional geogrids. A further increase in temperature may result in reaching values that may significantly affect the strength parameters of this material.

Studies confirm that in the aggressive environment of landfills, accelerated ageing of the material and reduction of mechanical parameters may occur. This is particularly important when a uniaxial geogrid is used in slopes landfills – which in extreme conditions – may lead to landslides and other threats to the environment.

CONCLUSIONS

Accelerated ageing tests of uniaxial HDPE geogrid incubated in water solution for 12 months simulating conditions at a municipal waste landfill at three temperatures (25°, 45° and 75°C) showed:

– The rate of antioxidant depletion depends on temperature (*OIT*). No antioxidant in the geogrid after 8 months of ageing tests at 75°C.
– No significant deterioration of the geogrid's mechanical parameters (tensile strength, relative elongation). Accelerated ageing tests at 75°C showed that the average elongation increased to 19.32% compared to 12.12% for the sample not subjected to accelerated ageing tests. The tensile strength did not change at 75°C.

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BADANIA TRWAŁOŚCI MATERIAŁÓW GEOSYNTETYCZNYCH STOSOWANYCH W TRUDNYCH WARUNKACH ŚRODOWISKOWYCH

STRESZCZENIE

W artykule opisano proces starzenia się georusztów z polietylenu o wysokiej gęstości (PEHD) pod wpływem czynników chemicznych i środowiskowych. Przedstawiono badania przyspieszonego starzenia jednokierunkowego georusztu PEHD inkubowanego w roztworze wodnym przez 12 miesięcy. Do przeprowadzenia przyspieszonych testów starzeniowych w roztworach wodnych symulujących warunki na składowisku odpadów komunalnych wybrano trzy wartości temperatury (25°C, 45°C i 75°C). Zmiany zarejestrowano za pomocą różnicowej kalorymetrii skaningowej (DSC), dzięki której sprawdzono także korelacje z właściwościami mechanicznymi starzonego georusztu. Nie zaobserwowano znaczącego wpływu ubytku przeciwutleniacza w tworzywie na właściwości mechaniczne georusztu jednokierunkowego. Badania pozwoliły na określenie właściwości mechanicznych takich jak wytrzymałość na rozciąganie i odkształcalność georusztu, cech niezwykle istotnych w analizie stateczności skarp.

Słowa kluczowe: testy przyspieszonego starzenia, degradacja utleniająca, wytrzymałość materiałów polimerowych, georuszty PEHD

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THE RISK OF CONTAMINATION OF THE FIRST AQUIFER IN THE CENTRAL PART OF THE ŚWIĘTOKRZYSKIE VOIVODSHIP (MHP-814 PIEKOSZÓW)

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ABSTRACT

The purpose of this study is to assess the local variation in the first aquifer's intrinsic vulnerability to pollution and identify potential sources of pollution that can affect groundwater quality. The analysis included 29 representative groundwater intakes from the map sheet MHP-814 Piekoszów (Świętokrzyskie Voivodship). A map was created with the marked intakes, the degree of their intrinsic vulnerability to pollution and existing hazards. Intakes potentially threatened by anthropogenic pollution were indicated. The compiled study has an informative function and can be used to make land use maps in municipalities, design protection zones, and create scenarios of threats to the groundwater intakes from specific pollution.

Keywords: groundwater intake, well, first aquifer, pollution, hazard, MHP-814

INTRODUCTION

Groundwater should be protected from anthropogenic contamination, as it serves as the primary source of providing the population with water suitable for drinking (Krogulec, Gurwin & Wąsik 2021; Woźnicka, Przytuła & Palak-Mazur, 2021). Legal protection under the Polish Water Law (Obwieszczenie Marszałka Sejmu Rzeczypospolitej Polskiej z dnia 14 października 2021 r. w sprawie ogłoszenia jednolitego tekstu ustawy – Prawo wodne) includes both the resources (quantity) and the chemical composition of groundwater. To ensure adequate water quality and protect their resources, protected areas are established for groundwater reservoirs and protection zones for water intakes. There is also an obligation to carry out agricultural production in a way that prevents the pollution of the waters with nitrogen compounds from agricultural sources (Department for Environment, Food and Rural Affairs [Defra], 2009). In addition, groundwater quality monitoring is carried out to report on the chemical status of groundwater, track its changes, and inform about risks on a national scale. According to the Water Law, monitoring is necessary to manage groundwater resources and assess the effectiveness of protective measures taken.

To plan appropriate actions for the protection of groundwater intakes, it is necessary to know the intrinsic vulnerability of the groundwater to contamination (Al-Mallah & Al-Qurnawi, 2018; Steiakakis, Vavadakis & Mourkakou, 2023). The intrinsic vulnerability determines the risk of migration of conservative contaminants from the ground surface to the first aquifer. Conservative contaminants do not undergo ion exchange processes with the soil–water environment or

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do not undergo biodegradation. Intrinsic vulnerability is related to the geological structure, the hydrogeological parameters and the aquifer recharge conditions of the aquifer. Recharge conditions depend on the aeration zone's thickness and the soil types through which contaminants migrate vertically from the land surface to the aquifer (Duda, Witczak & Żurek, 2011). Vulnerability classes were created based on the mean residence time (MRT), which is related to the exchange of water in the profile of the aeration zone during the natural hydrological cycle, assuming a multi-year average infiltration of annual precipitation (Duda et al., 2011). There are five vulnerability classes depending on the estimated seepage time (t_a) in years: A1 – aquifer at very high risk $t_a < 2$; A2 – aquifer at high risk t_a < 2−5 >; B – aquifer at medium risk t_a < 5−25 >; C – aquifer at low risk t_a < 25−100 >; D – aquifer practically not at risk $t_a > 100$.

According to the described methodology, a map of the intrinsic vulnerability to contamination has been created for Poland. Duda et al. (2011) prepared a map for assessing shallow groundwater of the first aquifer from the land surface (water table < 2 m) and a map for assessing the vulnerability of the major underground water reservoirs (abbreviation in Polish GZWP). The maps were made on an overview scale of 1:500 000 and are illustrative and strategic on the national scale. Available maps via GeoLOG application in the Central Geological Database (geolog.pgi.gov.pl), curated by the Polish Geological Institute − National Research (Institute Państwowy Instytut Geologiczny – Państwowy Instytut Badawczy [PIG-PIB], 2023a), first aquifer sensitivity and quality at a scale of 1:50 000 are based on different methodological assumptions, other source materials and different data preparation technology. Therefore, the local differences between the maps can be large. In the literature, there is a lack of work that considers the potential risk of contamination of individual groundwater intakes from existing sources of pollution. Duda et al. (2011) indicate the need to make them. Such studies would be useful for mapping land use planning, environmental protection and municipal water planning – including the establishment of protection zones for groundwater intakes. Identified intrinsic vulnerabilities of shallow groundwater to pollution can be used to create risk scenarios from specific contaminants, such as heavy metals. These, in turn, are subject to ion exchange processes in soils (Nartowska, Kozłowski & Kolankowska, 2017), which often lead to changes in soil properties (Nartowska, 2019) and weak protective barriers in landfills. It is important to note that the maps and overview scale do not take into account the potential hazards present on the surface of the land and therefore do not present a complete assessment of the risk of groundwater contamination (Liggett, Lapcevic & Miller, 2011). Potential sources of groundwater contamination include, but are not limited to, landfills (Koda et al., 2023; Podlasek, Vaverková, Koda, Jakimiuk & Martínez Barroso, 2023), agricultural land (Zhang, Qin, An & Huang, 2022), petrol stations (Bai et al., 2019) and industrial plants (Jain, Thakur, Garg & Devi, 2021).

Therefore, presented here is a study in which (i) the intrinsic vulnerability of the first aquifer to contamination was determined at 29 local deep wells within the hydrological map sheet of MHP-814 Piekoszów, Świętokrzyskie Voivodship; (ii) the radius of the water runoff area to each well intake has been calculated; (iii) hazards to groundwater intakes were identified.

MATERIAL AND METHODS

Characteristics of the study area

Location

Sheet MHP-814 covers parts of the municipalities of Łopuszno, Strawczyn, Piekoszów, Mniów, Małogoszcz Sitkówka – Nowiny, Chęciny, Radoszyce, and Miedziana Góra. The sheet area is bounded by coordinates 20°15'00" and 20°30'00" of east longitude and 50°50'00" and 51°00'00" of north latitude (Fig. 1). The area is a fragment of the Małopolska Highlands. In hydrographic terms, it is located in the river basin of the Nida, and its small fragments in the catchment areas of the Kamienna and Pilica rivers.

Hydrogeological conditions

Figure 2 shows the depth cartography of the study area. The disposable resources of this area are 347 m^3 per 24 h. The Triassic (T_1, T_2), Devonian (D_2), Permian (P_3) and Jurassic (J_3) horizons have the highest

Fig. 1. Topographic map of the study area

Source: PIG-PIB (2023a).

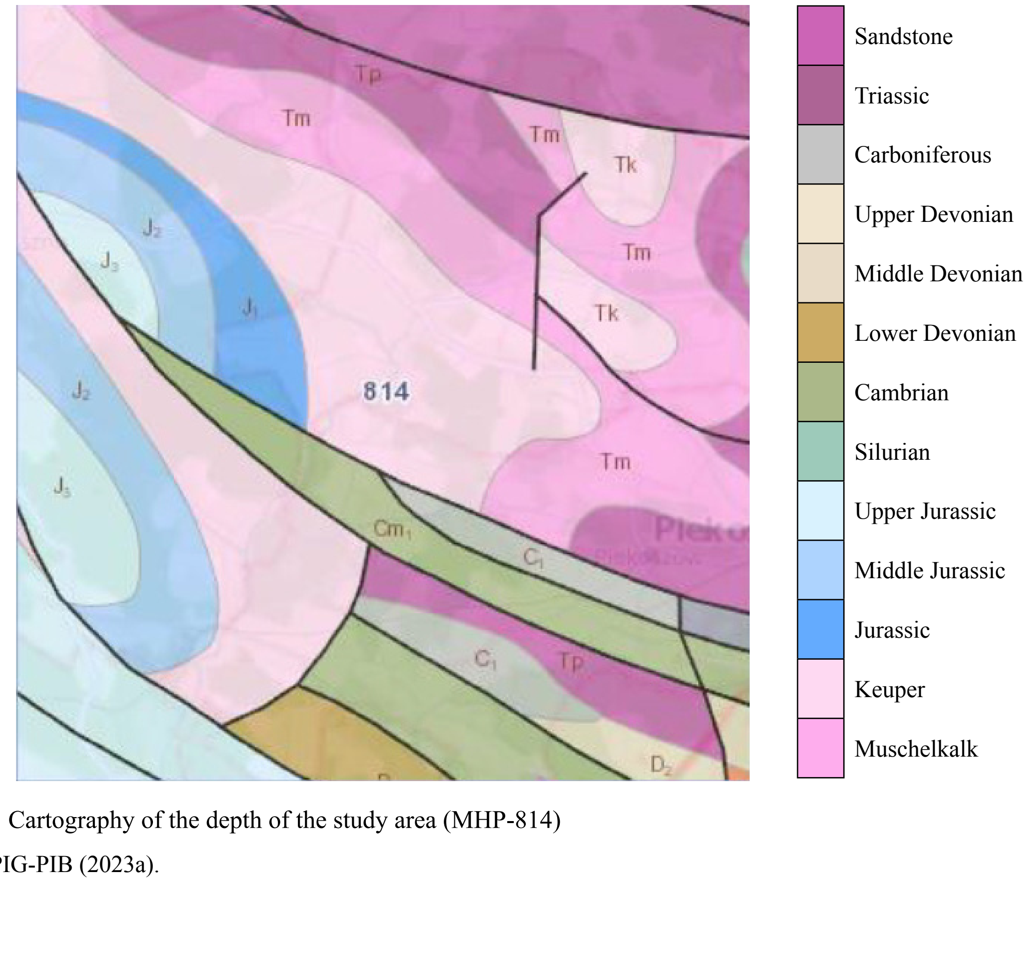


Fig. 2. Cartography of the depth of the study area (MHP-814)

Source: PIG-PIB (2023a).

groundwater potential (Table 1). The remaining 40% of the area is without prospective usable horizons (Prażak, 1997).

Within the sheet, three major underground water reservoirs are identified that require special protection: GZWP 414 Zagnańsk, GZWP 416 Małogoszcz and GZWP 417 Kielce (Fig. 3; Prażak, 1997).

In the area of sheet MHP-814, there is good quality. However, as a result of poor isolation between the surface layers of the ground and the aquifer, anthropogenic water contamination occurs in places and must be treated. Within Ruda Strawczyńska, there are increased indices of manganese and iron and – occasionally – nitrogen compounds, which are of a short nature (Prażak, 1997).

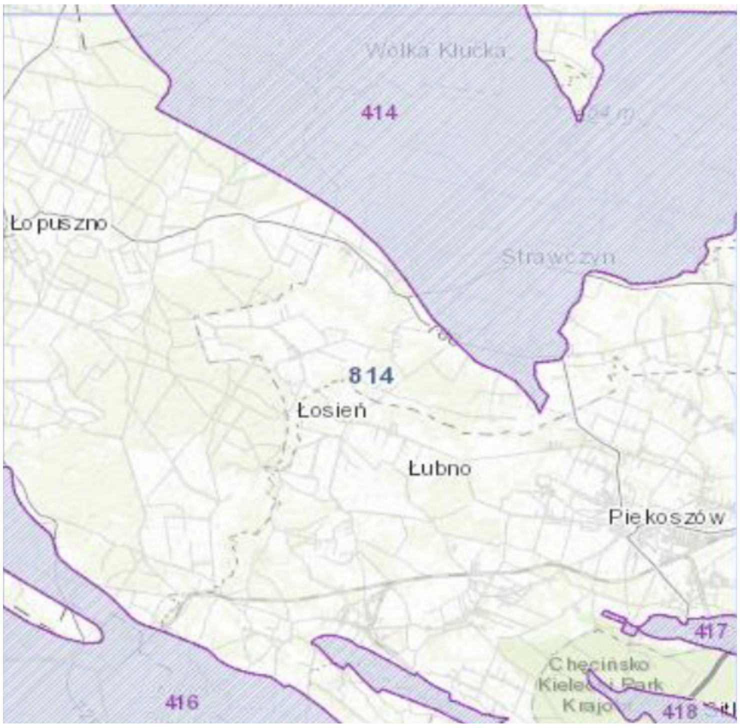
Methodology

The concentration of industrial activity in an area, including intensive groundwater exploitation and adverse hydrogeological conditions, are the main fac-

Table 1. Characterisation of aquifers of high utility significance, within sheet MHP-814

Stratigraphy/Lithology		Depth to aquifer [m]	Aquifer thickness [m]	Aquifer	Filtration coefficient [m·h^{-1}]
T_2	sandstones marls	5−20	10−100	unconfined	0.003−0.36
T_1	sandstones marls conglomerates	5−20	10−150	unconfined/confined	0.003−0.36
D_2	limestones dolomites	5−30	10−150	unconfined	0.003−3.6
P_3	sandstones marls conglomerates	5−15	10−150	confined	0.003−3.6
J_3	limestones, marls	5−30	10−150	unconfined	0.003−0.36

Source: own elaboration based on PIG-PIB (2023b).



GZWP 414
T_1, T_2 fractured-pore reservoir

GZWP 416
J_3 karstic fissure reservoir

GZWP 417
D_2, D_3 karstic fissure reservoir

Fig. 3. The major underground water reservoirs (abbreviation in Polish GZWP) that require special protection within sheet MHP-814 Piekoszów

Source: PIG-PIB (2023a).

tors that affect the threat to groundwater quality. It is possible to assess the potential threat that arises from the geological and hydrogeological structure of the site and the current threat that additionally arises from existing sources of pollution. The potential threat is determined by the vertical seepage of contaminants from the surface of the land into the aquifer (Krogulec, 2004; Krogulec & Trzeciak, 2017; Krogulec, Sawicka & Zabłocki, 2019). The method of assessing the intrinsic vulnerability of groundwater to contamination based on determining the migration time of conservative contaminants from the land surface to the aquifer is the method most commonly used in engineering practice alongside rank methods (Kondratiuk, 2013).

The MRT or the water exchange time (t_a) was calculated using the following formula (Witczak & Żurek, 1994; Duda et al., 2011).

$$t_a = \sum_1^n \frac{m_{ai} \cdot w_{0i}}{R}, \tag{1}$$

where:

m_{ai} – thickness of the vadose zone calculated for each layer of soil (i) [m],

w_{0i} – average volumetric water content of the strata in the vadose zone calculated for each layer of soil (i) [-],

R – mean annual recharge [mm] expressed as

$$R = P \cdot \omega_i, \tag{2}$$

where:

P – mean annual precipitation (700 mm in 1991––2020 was assumed) [mm],

ω_i – effective infiltration coefficient [-].

According to Macioszczyk (1999), the method proposed by Witczak and Żurek (1994) probably gives overestimated values for vertical seepage time. The reason may be that the formulas were verified by observations of the rate of transfer of chemical indicators, and this process is inherently slower due to the known phenomenon of 'lag'. However, the same author points out that the results were discussed in the Hydrogeology Committee of the Committee of Geological Sciences of the Polish Academy of Sciences, which appreciated the validity and the need to use the Witczak and Żurek (1994) formula for estimating the seepage time of conservative substances. The commission concluded that using the formula is useful, and sometimes even necessary, when organising the development of protective areas.

To assess the risk of threats from existing sources of pollution, the radius of the water runoff (abbreviation in Polish OSW) was calculated for each groundwater intake. The Sauta formula was used, which assumes radial inflow (Łońska, 2012):

$$r = 2.764 \cdot \sqrt{\frac{Q \cdot t}{m \cdot n_e}}, \tag{3}$$

where:

Q – well capacity [$m^3 \cdot h^{-1}$],

t – 9,130 [days] ≈ isochrone 25 [year],

m – thickness of the aquifer [m],

n_e – effective porosity (according to the graph of the relationship k to n_e in the publication by Pazdro, 2013, p. 110).

Identification of potential threats to groundwater intake was based on archival materials and the Central Geological Database (geolog.pgi.gov.pl), with its own verification. Agricultural land was also included in the study. The data on agricultural land was obtained from the land and building registry available in the Geoportal database (geoportal.gov.pl), curated by the Head Office of Geodesy and Cartography (Główny Urząd Geodezji i Kartografii [GUGiK], 2023).

RESULTS AND DISCUSSION

Table 2 and Figure 4 summarise the results for 29 local deep wells. Table 2 shows, but is not limited to, the intrinsic susceptibility of the first aquifer to contamination, the susceptibility class rating, and the radius of the water runoff to each well intake. In Figure 5, map was created with the location of the intakes and the existing sources of contamination.

Based on the analysis of the results in Table 2, Figures 4 and 5, the current risks for each well intake are presented. The results were included in Table 2 ('hazard' column). The hazard assessment

Table 2. Hydrogeological characteristics and assessment of hazards to groundwater intakes

No[1]	SHEET MHP-814 PIEKOSZÓW							
	No of well[2]	Location	PPW[3] [m]	t_a[4] [year]	Calculated risk class[5]	Q[6] [m^3·h^{-1}]	osw[7] [m]	Hazards[8]
1	8140002	Promnik	11.5	1.72	A1	8	185.8	petrol station
2	8140003	Oblęgorek	23.2	4.76	A2	16	370.9	
3	8140004	Łopuszno	7.8	1.72	A1	0.1	42.7	petrol station, sewage plant
4	8140005	Oblęgorek	11.7	2.65	A2	2.4	151.3	
5	8140010	Piekoszów	46	0.08	A1	96.6	801.1	industry: meat
6	8140011	Jaworznia	36.4	0.42	A1	5.4	197.3	industry: limestone powder
7	8140020	Gnieździska	6	1.51	A1	0.1	65.3	farmland!
8	8140023	Snochowice	13	0.11	A1	0.1	36.8	
9	8140027	Cierchy	47	1	A1	96.6	763.8	
10	8140028	Strawczyn	19.3	3.31	A2	2.2	131.9	
11	8140036	Piekoszów	15.6	7.98	B	181.5	676.1	garden farm 'Zajączków'!
12	8140038	Strawczyn	9.6	2.85	A2	83.7	567.2	
13	8140040	Gnieździska	25	0.98	A1	2.4	191.8	farmland!
14	8140041	Piekoszów	86	120.9	D	153	1 111.4	
15	8140042	Micigózd	22.3	0.23	A1	3.1	301	industry: meat
16	8140044	Oblęgorek	31.5	37.28	C	1.2	181.7	
17	8140046	Skoki	42	12.52	B	5.1	321.6	
18	8140050	Wesoła	7	1.9	A1	6	239.3	farmland!
19	8140051	Jaworznia	29.5	6.45	B	3	183.7	
20	8140052	Piaski	56	75.66	C	5.4	256.2	
21	8140053	Gnieździska	10.5	0.34	A1	54.7	327.1	
22	8140056	Rykoszyn	0.9	0.16	A1	4.7	242.2	
23	8140057	Gnieździska	17.2	0.93	A1	234.4	1 308.6	
24	8140059	Rykoszyn	22	21.02	B	2	217.1	
25	8140064	Wielebnów	29.2	1.61	A1	33.8	496.9	
26	8140066	Laskowa	0.4	1.59	A1	2.3	207	industry: meat, petrol station
27	8140067	Ruda Str.	45	5.33	B	26.3	204	
28	8140069	Laskowa	71.5	0.07	A1	73.3	422.3	industry: meat, petrol station
29	8140071	Zawada	28	9.13	B	12.5	183	

[1]Cardinal numbers.
[2]Number according to the database of the Polish Geological Institute – National Research Institute (geolog.pgi.gov.pl).
[3]Depth to the first aquifer (abbreviation in Polish PPW).
[4]Average water migration time from the ground surface to the first aquifer in years according to Eq. (1).
[5]A1 – $t_a < 2$; A2 – t_a < 2–5 >; B – t_a < 5–25 >; C – t_a < 25–100 >; D – $t_a > 100$ years (Duda et al., 2011).
[6]Capacity of wells.
[7]Radius of the water runoff area according to Eq. (3).
[8]Potential hazards to groundwater intakes.

Source: own work.

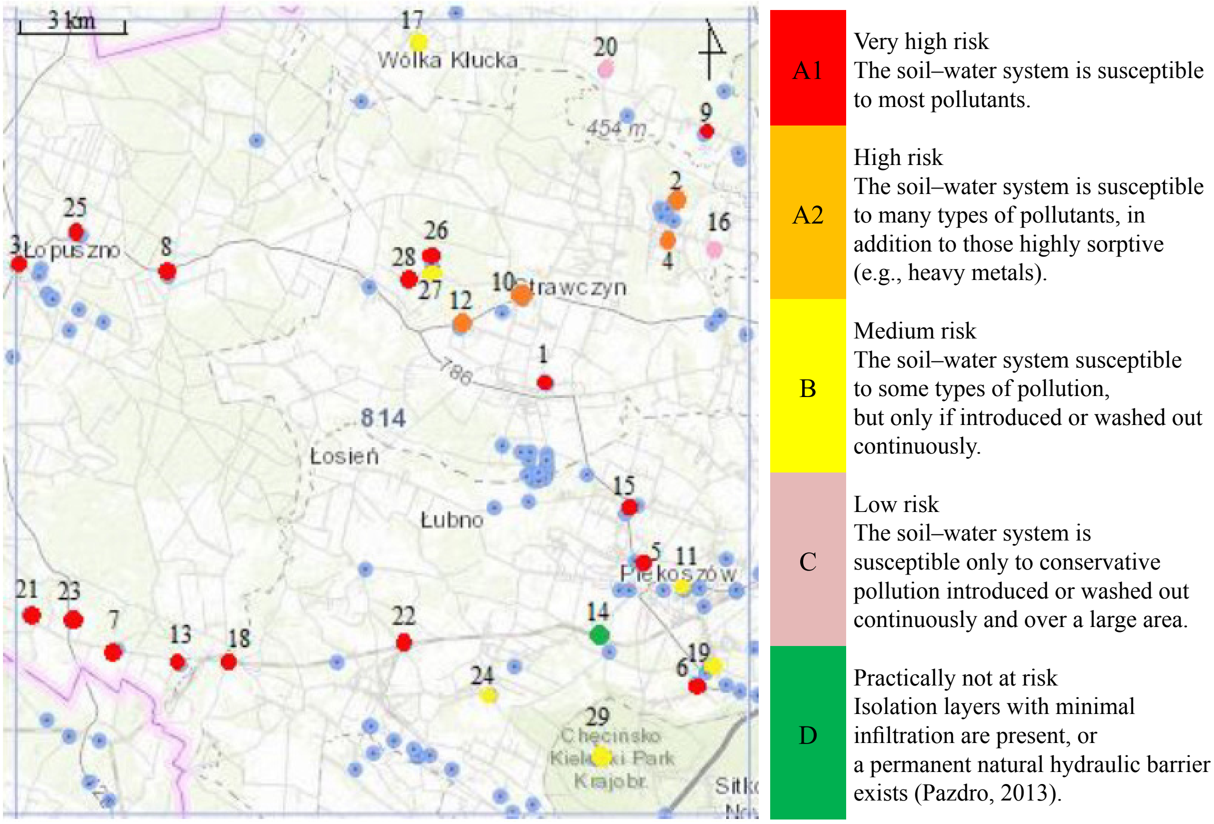


Fig. 4. Location of groundwater intakes with assigned vulnerability class. Nos 1–29 are consistent with the intake numbers in Table 2

Source: own elaboration based on PIG-PIB (2023a).

considered the class of vulnerability of the aquifer to contamination, the radius of the water runoff area to the intake and the distance from potential pollution sources.

Within MHP-814 Piekoszów map sheet, the occurrence of agricultural land was identified within the runoff of water to intakes Nos 8140057, 8140020 and 8140050. The well intakes are very highly at risk (A_1). In these areas, more detailed studies are required to establish or change the extent of protection zones.

The threatened area also includes intake No 8140036, and the radius of water runoff to the intake includes the nearby horticultural farm 'Zajączków'. The intake is classified as moderately at risk. The need to control the quality of the water in this intake for possible contamination, such as fertilisers, is indicated. Due to the very high intrinsic vulnerability of the aquifer to contamination, the presence of industrial plants or petrol stations within the runoff of water to the intake Nos 8140002, 8140004, 8140010, 8140011, 8140042, 8140066 and 8140069, it is recommended that the quality of these aquifers be monitored or protective steps be taken.

The other groundwater intakes do not have a very high vulnerability class, or no anthropogenic hazards have been identified within them.

The results are difficult to compare because this is probably the first study for individual intakes that shows local variation and takes into account existing sources of pollution. Considering only the degree of vulnerability of aquifers to contamination, a high

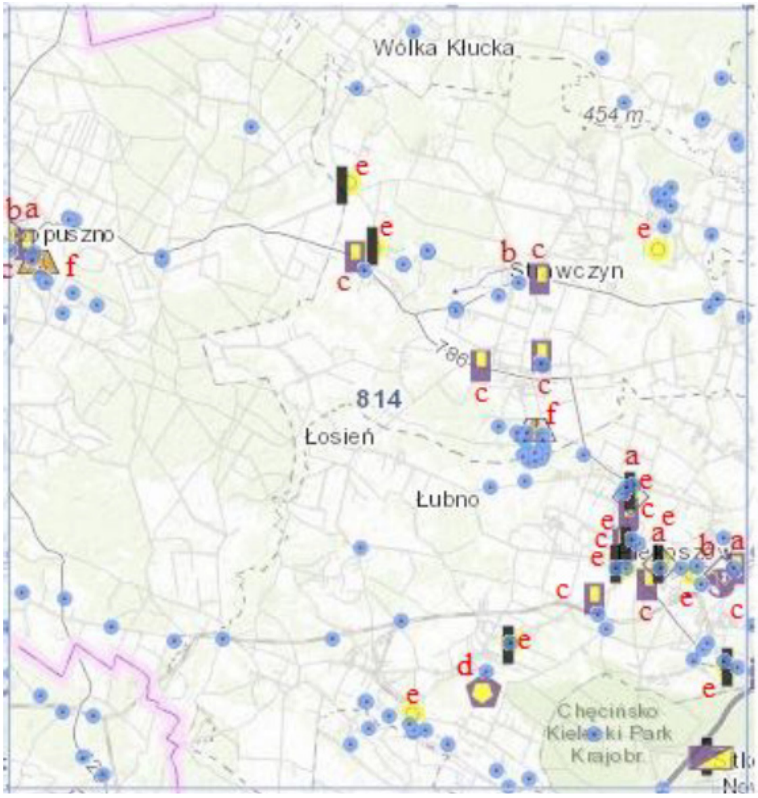


Fig. 5. Location of potential pollution sources for groundwater intakes

Source: own elaboration based on PIG-PIB (2023a).

degree of convergence with the map 'first aquifer sensitivity and quality' at a scale of 1:50 000 is visible. This is unexpected, as the creation of this map was based on different methodological concepts (Duda et al., 2011).

CONCLUSIONS

This study identifies risks to the quality of the first aquifer of groundwater intakes from the MHP-814 Piekoszów map sheet. In the assessment of the risk of contamination, the following were taken into account: the natural vulnerability of water to contamination, the radius of the runoff area to the intake and existing sources of pollution.

Based on the above factors, intakes particularly at risk were selected – which require concrete actions toward their protection: monitoring, modification of protection zones, elimination of pollution sources or, at least, further research.

The following hazards were selected for the study area for specific numbers of water intakes: agricultural lands (Nos 8140057, 8140020 and 8140050), horticultural farm 'Zajączków' (No 8140036) and industrial plants or petrol stations (Nos 8140002, 8140004, 8140010, 8140011, 8140042, 8140066 and 8140069).

The study is informative for the local community and local governments. The scale of groundwater contamination in Poland should contribute to increasing public attention to its protection and the consequences that our passivity and ignorance can cause. Today, educating and encouraging the cooperation of all stakeholders and the local community is important so that the state of the waters improves, guaranteeing adequate quantity and quality for future generations.

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RYZYKO ZANIECZYSZCZENIA PIERWSZEJ WARSTWY WODONOŚNEJ W CENTRALNEJ CZĘŚCI WOJEWÓDZTWA ŚWIĘTOKRZYSKIEGO (ARKUSZ MHP-814 PIEKOSZÓW)

STRESZCZENIE

Celem badań jest ocena lokalnego zróżnicowania podatności właściwej płytkich wód podziemnych na zanieczyszczenia oraz wskazanie potencjalnych źródeł zanieczyszczeń, które mogą wpłynąć na jakość wód podziemnych. Analizie poddano 29 reprezentatywnych ujęć wód podziemnych z arkusza MHP-814 Piekoszów, województwo świętokrzyskie. Stworzono mapę z zaznaczonymi ujęciami oraz stopniem ich podatności na zanieczyszczenia wraz z istniejącymi ogniskami zanieczyszczeń. Wskazano ujęcia potencjalnie zagrożone. Sporządzone opracowanie pełni funkcję informacyjną i może być wykorzystane w celu wykonania map zagospodarowania przestrzennego w gminach, projektowania stref ochronnych ujęć oraz tworzenia scenariuszy zagrożeń zanieczyszczeniami specyficznymi dla analizowanych ujęć wód podziemnych.

Słowa kluczowe: ujęcie wód podziemnych, studnia, pierwsza warstwa wodonośna, zanieczyszczenie, zagrożenie, MHP-814

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LOSS OF RIVER NATURALNESS – CAUSES AND CASES

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ABSTRACT

The economic growth of lowland areas is closely related to water management, with the development of valley areas limited by local hydrological conditions. The water retention shaped by hydro-technical structures enables the subsequent use of water for flood protection, agricultural, industrial, fire-fighting, energy, or recreational purposes, conditioning the potential development opportunities of the region. Over the years, there have been different approaches to the exploitation of water resources – from total subordination of nature by man to the development of sustainable solutions. However, to utilise the potential of rivers, channels and valleys were subjected to regulation, which in some cases provided immediate economic benefits, but in the long-term, deprived the river of its natural qualities, inhibiting its ability to self-purification morphodynamic processes. The water runoff acceleration as a result of channel straightening and concreting, combined with the narrowing of river valleys, led to a progressive increase in flood risk. As observed, over the years, such rivers increased the flood problem, oppositely to intentions. In response to deteriorating hydromorphological conditions, a variety of mitigation measures have been undertaken, which can be broadly termed as river restoration. The article presents the most common causes leading to the loss of naturalness, one of the most significant environmental effects. As demonstrated, most often, the loss of naturalness of water occurs through the influence of several factors, although in individual cases, it is possible to recognise one of them as the main threat source.

Keywords: river restoration, natural river, river habitat, water contamination, pollution, river water quality

INTRODUCTION

The river's natural status loss is particularly the result of various activities and treatments carried out in channels and valleys or is related to the water quality. The recognised causes for the impoverishment of river reach naturalness usually play a major role in the decision of a restoration project, its main direction, and the advancement of included activities (Żelazo, 2006).

Natural rivers in a properly managed landscape are a stable and self-sustaining part of the environmental water cycle. A regulated river whose channel is straight and uniform in depth, and whose banks are devoid of shady trees and shrubs, loses its status as a naturally formed ecological habitat, as well as increases the dynamics of flood discharges and impairs retention capacity during drought periods. The achievement of the intended objectives of river regulation, such as land drainage and flood protection, the provision of significant water quantities, and the improvement of waterway transport conditions required specialised hydraulic work and the introduction of drainage works. The undertaking of extensive hydraulic engineering measures to regulate rivers has taken place almost all over the world and has generally formed the basis of economic prosperity. The article presents the most

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common causes leading to the partial impoverishing or total loss of river naturalness. It demonstrates that it derives from the influence of several factors, although in individual cases, it is possible to recognise one of them as the main threat source.

RIVER ECOLOGICAL STATUS SPECIFICATION

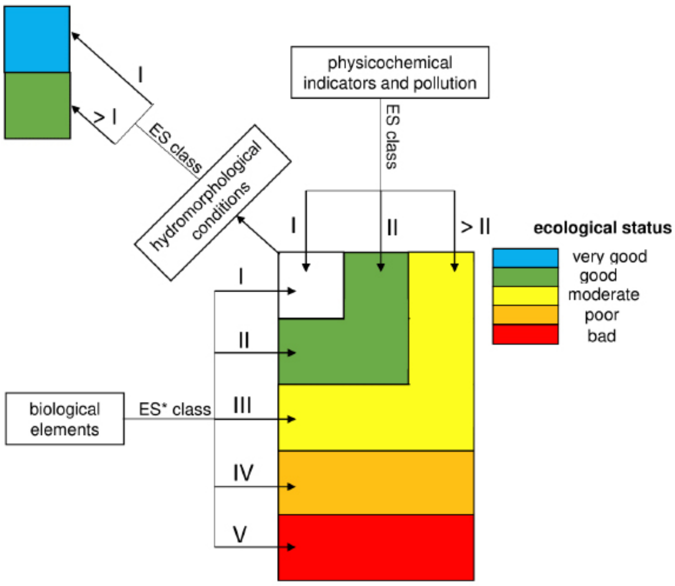
Surface water body status evaluation (of rivers, lakes, transitional, and coastal water bodies) is determined by environmental monitoring and presented as an ecological and chemical status assessment. Within EU countries, the ecological status of surface water bodies can be classified by assigning one of five quality classes. Good water body status could be recognised if the habitat is relatively close to the natural condition. The obligation to study and assess the quality of surface waters arises from Article 349 of the Polish Water Law (Ustawa z dnia 20 lipca 2017 r. – Prawo wodne). The rules for the classification and assessment of the status of surface water bodies in Poland are contained in the Regulation of the Minister of Environment of 21 July 2016 on the classification of surface water bodies and environmental quality standards for priority substances (Rozporządzenie Ministra Środowiska z dnia 21 lipca 2016 r. w sprawie sposobu klasyfikacji stanu jednolitych części wód powierzchniowych oraz środowiskowych norm jakości dla substancji priorytetowych) and the Regulation of the Ministry of Environment of 9 November 2011 regarding ecological state classification, ecological potential and chemical state of the surface water bodies (Rozporządzenie Ministra Środowiska z dnia 9 listopada 2011 r. w sprawie klasyfikacji stanu ekologicznego, potencjału ekologicznego i stanu chemicznego jednolitych części wód powierzchniowych). According to the Polish Water Law, the implementation of surface water monitoring is aimed at obtaining information on surface water status for management and achieving environmental objectives. The ecological status characterises the quality of structure and functioning of the aquatic ecosystem and is determined by the following groups of elements: biological, physicochemical, and hydromorphological indicators. Both hydromorphological and physicochemical elements are supporting groups for the set of biological elements (Żelazo, 2006).

THE NATURAL STATUS OF A RIVER AND ITS VALLEY

The river's naturalness is gradable value – a river or any other land use object may be more or less natural. The assessment of anthropological influences on the hydromorphological regime serves to recognise the proximity to the natural state of the habitat. An undisturbed or insignificantly disturbed state will indicate a high degree of channel naturalness.

From an engineering perspective, a river is natural when it has not been modified by channel regulation works or any other river engineering activities (Żelazo, 2006). The natural characteristics of rivers, adjacent valleys, and catchments, can be divided as follows:

1. Adequate purity and quality of flowing and standing waters. It should be emphasised that the biological quality of water has an overriding value in the process of ecological status assessment. A river cannot achieve a very good ecological status when biological elements have reached a status lower than very good (Fig. 1).
2. The function of waters as a habitat, providing conditions suitable for life and development of aquatic organisms: water bodies without abiotic features are transformed into almost unsettled or completely degraded watercourses, which cannot carry out self-purification processes. Such rivers are also deprived of any space that could create the possibility to form feeding grounds for biodiversity inhabiting the aquatic space, refuges, enclaves, spawning places, and others. Natural riverbeds are characterised by elements such as variation in river depth, cross-section shapes, longitudinal profile shapes, or alluvial bed formations resulting from sediment and debris transport (Fig. 2).
3. A significant role in landscape shaping, as well as natural and recreational-touristic values: this aspect is strongly correlated with the naturalness of the horizontal distribution of the river network and its bed structure, as well as with the river valley development and shape properties, with the specificity of slopes and vegetation presence.



ES – ecological status

Fig. 1. Ecological status classification scheme

Source: own work based on the Common Implementation Strategy for the Water Framework Directive (Directive 2000/60/EC).

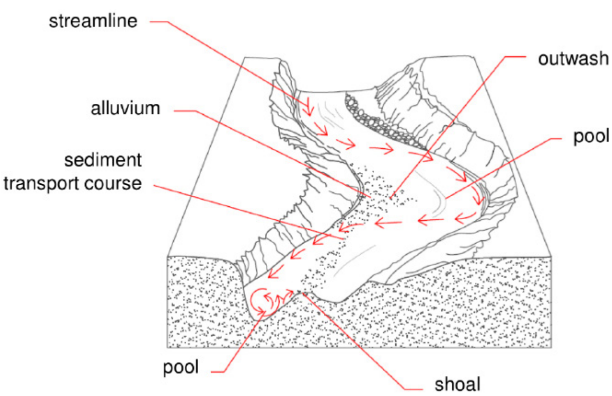


Fig. 2. Unregulated river and its hydromorphological elements

Source: own work.

CAUSES OF NATURAL STATUS LOSS

For a variety of reasons, the naturalness of rivers and their valleys has been lost. The majority of them were caused by total watercourse modifications connected with river regulation, involving such actions as:

- straightening of river channels (Fig. 3);
- standardisation of cross-section dimensions and shapes;
- elimination of irregularities of the river bed and banks;
- the devastation of ecotone vegetation (Fig. 4);
- elimination of connections between the old river bed and the main channel;
- an increase of slopes;
- duration and range of floods diminishing.

The main source of river pollution is sewage, both domestically discharged from cities and settlements, and all types of industrial and agricultural sewage. However, the most toxic wastewater from industry carries a lot of heavy metals, nitrates and phosphates, petroleum substances, phenols, cyanides, benzene, and formaldehyde (Kulikauskaitë & Paliulis, 2015; Grabiec & Kurpisz, 2020). The consequences of their presence and further reactions are huge losses in river ecosystems and the accumulation of toxins in animal bodies.

Another group of river pollution is debris, which is formed by the sedimentation of mineral and organic suspensions resulting from previous erosion and constituents precipitated from the flowing water. In many

Fig. 3. Straightened river bed – the Zagożdżonka river in central-eastern Poland

Source: photo by Marta Kiraga, summer 2013.

Fig. 4. Scorched shoreline vegetation – the Zagożdżonka river in central-eastern Poland

Source: photo by Marta Kiraga, winter 2012.

cases, debris formation also involves material delivered with municipal and industrial wastewater and carried by surface runoff from urbanised, industrial, and agricultural areas (Madeyski, 2007; Wichowski, Nowak & Rutkowska, 2017). Aquatic debris stores most of the potentially harmful metals (including copper, zinc, nickel, chromium, lead, cadmium, and mercury) and organic compounds that enter surface waters. River sediments also accumulate persistent organic pollutants (POPs), including polycyclic aromatic hydrocarbons (PAHs) and organochlorine compounds such as organochlorine pesticides and polychlorinated biphenyls (PCBs), (Bach, Röpke & Frede, 2005).

River waters lost their naturalness not only as a result of improperly planned regulation but also through any unfavourable works within the channel and the valley. The most important causes leading to naturalness deterioration include (Table 1):

- works in the catchment area leading to an increase in flood discharges, e.g. deforestation, drainage works, degradation of landscape retention, development of urbanisation and transport infrastructure as well as watercourses regulation (Khalegi, 2017);
- activities leading to a decrease in flood discharges due to the construction of too many artificial retention reservoirs (Mei, Van Gelder, Dai & Tang, 2017);
- too frequent equalisation of water surface levels and discharge variability, which reduces their dynamics; accumulation of river sediment upstream of weirs or barrages has unfavourable consequences for the dammed river sections (Galay, 1983);
- introduction of alien fish species to the waters, which are unsuitable for a given river, which causes a threat to native species (Meixler, Bain & Walter, 2009);
- preventing mass migrations of fish and other aquatic organisms along the river by installing sills or weirs (Meixler et al., 2009);
- undertaking maintenance works that are too frequent or too extensive, or that are completely unnecessary and consist in the elimination of the riverbed morphological diversification (elimination of islands, stone sills, and sediment bedforms), unification of banks, and devastation of vegetation (Buckley & Crone, 2008; Normile, 2010);
- carrying out maintenance works on a small scale, which is insufficient for a given river, which results in an intensive process of erosion and degradation of the riverbed;

Table 1. Causes for a loss of naturalness in river ecosystems

Construction processes and site organisation causes	Hydraulic engineering development causes
deforestation	development of urbanisation and transport infrastructure
drainage works	embankments
degradation of landscape retention	watercourse regulation
elimination of ponds and oxbow lakes in floodplains by filling them with soil from the foundation trench	construction of too many artificial retention reservoirs, weirs, barrages, sills, etc.
destroying and draining wetlands	introduction of alien fish species
excessive ground compaction	preventing mass migrations of fish and other aquatic organisms along the river by installing sills, weirs, and dams
machinery and vehicle movement on the site	too frequent or too extensive maintenance works
erosion processes occurring downstream of the construction site	insufficient scale of maintenance works
drainage of the subsoil	elimination of ponds and oxbow lakes
conducting tree and shrub clearing to provide space for construction facilities	–

Source: own work base on: Galay (1983), Gibbs (2000), Kaufman (2000), Buckley and Crone (2008), Meixler et al. (2009), Alonso and Cardoso (2010), Normile (2010), Winemiller (2010), Verachtert, Maetens, Eeckhaut, Poesen and Deckers (2011), Bai et al. (2013), Khalegi (2017), Mei et al. (2017), Wiekenkamp, Huisman, Bogena and Vereecken (2020).

- elimination of ponds and oxbow lakes by filling them with soil (Żelazo, 2006);
- destroying and draining wetlands (Gibbs, 2000; Bai, Cui, Cao, Li & Zhang, 2013);
- planting trees unsuitable for valley conditions (Żelazo, 2006).

The loss of water body naturalness also occurs as a result of works related to the implementation of various hydraulic and wastewater facilities, accompanied by the construction site organisation process. The thread for natural habitat value can be divided into two components – direct causes invoked by the structure introduction itself and causes related to the entire construction cycle. The main causes related to the construction cycle include:

- excessive compaction of the ground resulting from machinery movement and any vehicles on the site, soil storage, and the storage of construction materials and equipment (Wiekenkamp et al., 2020);
- erosion processes occurring downstream of the construction site (Kaufman, 2000);
- works related to the drainage of the subsoil, leading to a lack of water in wells in the adjacent area, excessive area drying, as well as to the collapse of that area (Alonso & Cardoso, 2010; Verachtert et al., 2011).

MITIGATING EFFORTS

The first step to protect the river that has been regulated is to subject it to restoration works. These are activities aimed at restoring or approximating the natural character of the watercourse with the appearance of greater species diversity and increased effectiveness in the fight against excessive anthropopressure. One of the important activities responsible for water quality is minimising the need for soil fertilisation. Water restoration projects should include activities improving water purity itself. These are properly initiated, stimulated, and intensified biological and chemical processes that take place in the significant presence of organisms. Technical undertakings may include:

- habitat modifications that increase the share of naturally occurring processes, for instance, conversion of erosion-inhibiting steps to ramps that allow aquatic organisms to communicate, and the removal of impermeable barriers;
- works that, when completed, do not create a finished element of a restored habitat, but initiate a natural process that is supposed to return the river to its natural state, such as vegetation introduction;
- maintenance works, which consist of minor corrections to the natural transformation of the river, not aimed at natural habitat creation, such as fallen trees and replenishment of bushes;
- maintenance of water quality in the course of restoration (care and maintenance procedures, protection and improvement of its quality);
- abandoning some maintenance activities and leaving them to the influence of nature; therefore, rivers may undergo transformations that bring them closer to nature due to morphodynamic channel processes, beaver activities, the imapct of vegetation, etc. (Żelazo, 2006).

Therefore, the process of river restoration could be generally divided into three basic stages: initiation activities, which aim to provide the right conditions for the restoration process to begin; spontaneous activities carried out by nature; conservation works, monitoring, and supervision.

Restoration activities serve to create a living space for aquatic organisms as well as because they lead to improving the natural purity of water. Surface water restoration is an example of increasing natural retention possibility, which is realised by measures aimed at protecting water resources by restoring or maintaining natural ecosystems. Such measures contribute significantly to reducing the losses incurred by society, the environment, and the country's economy as a result of climate change, constituting one of the possibilities for adaptation to climate change.

Surface water restoration includes, therefore: improvement of channel and valley retention, normalisation of water relations in the catchment, wetlands, and peat bog restoration, as well as restoration of continuity and hydromorphological diversity of watercourses and lakes. Such activities improve habitat resilience, that is, the adaptation of ecosystems and the continuity of services provided by them. Water restoration reduces flood risk, mitigates the drought effects, reduces the necessary costs of maintenance works, and creates socially attractive places.

The studies on surface water quality result from the legislation (Directive 2000/60/EC, as well as regional legal frameworks, such as the Polish Water Law or French Legislative Framework) in the scope of physicochemical, chemical, and biological elements. The idea of conducting such studies is to increase and disseminate knowledge on the ecological and chemical status of water bodies. To obtain a habitat with a high ecological status, it is necessary to undertake activities aiming to improve its hydromorphological condition, as well as to protect waters against industrial pollution, including salinity and substances especially harmful to the aquatic environment, leading to eutrophication. Implementation of water quality monitoring and other planned activities is carried out according to the water management cycle described in regional legislation.

To protect the hydromorphological status of water as well as its quality, the following measures could be undertaken:

- reducing the use of artificial fertilisers and plant protection products on farms and in households in favour of fast biodegradable products, as well as the use of cleaning products containing lower amounts of phosphorus;
- abandonment of discharging wastewater into waters or land, which contributes to the construction of sewage networks and new wastewater treatment plants;
- reconstruction and improvement of existing wastewater treatment plants and investment in new cleaner technologies;
- discharging only treated wastewater into waters or land;
- treating and desalinating mine and road water, leading to a reduction of salt used for gritting roads and pavements during winter;
- applying geotextiles to separate landfills and waste dumps from groundwater and surface water;
- basing on new, safe industrial technologies and modernising environmentally unfriendly technologies: using closed water circuits, building treatment plants, and using more efficient filters.

Spontaneous river regulation, which is the natural river activity in the process of restoration, contributes

a

b

Fig. 5. Examples of river regulation based on natural materials: a – the Barranco Mogán river (Puerto de Mogán, Gran Canaria) fortified with stone rubble with a fraction more than 25 cm; b – the Szum river (Aleksandrów, Lubelskie Voivodship, Poland) fortified with stone rubble with a fraction less than 25 cm

Source: photo by Anna Maria Remer, summer 2019.

to the achievement of greater variation in both spatial and species diversity. The spatial abiotic features that have diversified as a result of spontaneous restoration are water velocity and depth, the grain size of the riverbed material, and access to light and oxygenation. In turn, the increase in species diversity is due to the diversification of habitat conditions so that the development of different biocoenoses occurs, leading to an ecological status improvement. However, spontaneous river restoration is a very long-term process and usually does not guarantee the complete restoration of morphological and biocenosis characteristics of the natural river habitat.

Regulation activities do not always have to result in river environment degradation. Sustainably conducting regulation and maintenance works consists of applying environmentally friendly measures that allow achieving the assumed technical objectives while limiting the negative effects. Examples of environmentally friendly materials are wood, natural stone (Fig. 5), and fascine – including regrowth naturally present in habitats elements such as large boulders or tree trunks and stumps.

CAUSES FOR THE LOSS OF NATURAL FEATURES USING THE EXAMPLE OF SELECTED LOWLAND RIVERS

In the past, a large number of small lowland rivers in Europe were regulated. Such changes generally led to improved water management. Unfortunately, regulation activities also caused adverse changes in the natural environment of rivers and their valleys. A loss of naturalness often occurred in situations leading to significant modification of a watercourse, such as new river channel creation.

Examples of works carried out on rivers, assuming mainly regulation activities, as a result of which the waters lost their naturalness are:

- The Prosna river in Kalisz (Poland, Wielkopolskie Voivodship) – the regulation of the river consists of straightening, narrowing, and unifying the longitudinal inclination of the bottom of the river as well as strengthening banks by covering them with concrete slabs. The result of these actions is a complete deprivation of the river flora and aquatic fauna (Małecki & Wira, 2011).
- The Wierchomlanka river near its confluence with the Poprad river (Poland, Małopolskie Voivodship) – the stream was regulated by completely unifying its channel by levelling the bed and by introducing concrete elements. Straightening of the naturally meandering riverbed contributed to the flow of large water increment, and its concreting resulted in the disappearance of aquatic organisms. Regulatory works also included covering the banks with perforated panels, which was associated with the devastation of shoreline vegetation (Froehlich, 1980).
- The Isenach channel in Carlsberg (Germany, Rhineland-Palatinate) – the channel regulation was performed by creating an artificial channel embanked by stones, narrowing its cross-sections at a certain reach, as well as standardising the cross-section. These actions resulted in a faster stream, which also led to higher peak flows. The scope of regulation works includes completely removing one of the banks and replacing it with a vertical wall made of gabions. The newly created river is completely devoid of vegetation and aquatic organisms, which additionally affects the loss of its naturalness.
- The Emscher river in Oberhausen (Germany, North Rhine-Westphalia, Westphalia) – the river regulation consisted of levelling the river bed and straightening it, which leads to faster runoff and higher flood risk. The regulation works on the Emscher also included the unification of the banks' inclination, which made the river symmetrical in cross-section (Hemmings & Kagel, 2010).

CONCLUSIONS

Rivers staying in a natural state constitute habitats that occur naturally in the environment. From a morphodynamic point of view, they result from fluvial processes occurring in nature. These rivers are also characterised particularly by the absence of pollution by foreign waters and other toxic substances and by the fact that suitable animals and plants can live and grow in these habitats. A river in its natural state has not been modified by regulation or other river engineering projects but has been shaped by the forces of nature. The naturalness of a river and its valley is characterised by three basic features: the purity of water (quality), its ability to function as a living space and its important role in shaping the landscape, and its aesthetic and recreational values.

The most significant problem is that in the past, regulation was mainly carried out from a technical point of view. According to the development directions at that time, environmental aspects were not adequately considered or, at worst, were completely neglected. Technical river regulation was popular due to an overriding role of water management towards economic growth and development of non-urbanised areas with the prevailing fashion of straightening rivers – unjustified, as we know it today. Therefore, technical regulation was carried out on a large scale, as were the consequences of these activities causing adverse effects on the aquatic environment. In addition to the impact of hydraulic works and the introduction of water structures, the loss of river habitat naturalness is very strongly and negatively affected by various external factors. One of the most dangerous of them is the introduction of water polluted in a mechanical, chemical, or biological way into rivers, lakes, or other water bodies.

The basic aims of water ecosystem management are to protect it from the inflow of pollutants (sewage) and to improve the quality of already polluted waters (re-naturalisation). Another activity carried out in the field of protection of waters and their naturalness is restoration works – recovering the naturalness or approximation to the natural status of regulated river habitats. Water body management also includes carrying out environmentally friendly maintenance works, which ensure safe and natural methods of watercourse regulation.

The beginning of natural feature disappearance usually takes place at the construction project realisation stage, and it occurs immediately after the building process begins. Over the following years, the loss of naturalness is strongly influenced by factors that harm the environment for longer and slower. The main reason for the loss of naturalness of flowing and standing waters is the undertaking of reasonable and previously planned activities leading to economic benefits without considering the environmental aspect of the operation.

Authors' contributions

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

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UTRATA NATURALNOŚCI RZEK – PRZYCZYNY I PRZYKŁADY

STRESZCZENIE

Wzrost gospodarczy na obszarach nizinnych jest ściśle związany z gospodarowaniem wodą. Ograniczeniem rozwoju obszarów dolinowych są m.in. lokalne warunki hydrologiczne. Retencja kształtowana przez budowle hydrotechniczne umożliwia późniejsze wykorzystanie wody do celów przeciwpowodziowych, rolniczych, przemysłowych, przeciwpożarowych, energetycznych czy rekreacyjnych, warunkując potencjalne możliwości rozwoju regionu. Na przestrzeni lat stosowano różne podejścia do eksploatacji zasobów wodnych – od całkowitego podporządkowania przyrody człowiekowi po opracowanie zrównoważonych rozwiązań. W celu wykorzystania potencjału rzek kanały i doliny poddawano regulacji, która w niektórych przypadkach przynosiła doraźne korzyści ekonomiczne, ale w dłuższej perspektywie pozbawiała cieki wodne naturalnych walorów, hamując zdolność do samooczyszczania lub procesy morfodynamiczne zachodzące w korycie. Jak zaobserwowano, problem powodzi jest wciąż często spotykany i uciążliwy, pomimo prowadzonych działań z zakresu inżynierii wodnej i w opozycji do jej zamierzeń. W odpowiedzi na pogarszające się warunki hydromorfologiczne podejmowane są różnorodne działania łagodzące, które można ogólnie określić mianem renaturyzacji rzek. W artykule przedstawiono najczęstsze przyczyny prowadzące do utraty naturalności, mające najistotniejsze skutki środowiskowe. Jak wykazano, najczęściej utrata naturalności wód następuje w wyniku oddziaływania kilku czynników, choć w pojedynczych przypadkach możliwe jest uznanie jednego z nich za główne źródło zagrożenia.

Słowa kluczowe: renaturyzacja rzek, rzeka naturalna, siedlisko dolinowe, zanieczyszczenie wód, odpady, stan rzeki

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REVIEW PAPER

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TRANSFORMING URBAN FOOD SYSTEMS THROUGH AGROECOLOGY – A REVIEW OF AGROECOLOGICAL PROJECTS IN MADRID IN TERMS OF THE MUFPP FRAMEWORK

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ABSTRACT

The paper discusses an agroecological approach to an urban food system's transformation. A selection of representative initiatives and projects in Madrid were analysed. The goal of the paper is to review these projects and identify their potential in the context of transforming Madrid's food system into a sustainable one, according to the Milan Urban Food Policy Pact (MUFPP) framework. The following methods were used in the study: (i) desk research – a review of academic papers and press materials provided by the various entities working on the transformation of Madrid's food system; (ii) case studies – field visits, participatory observation, and interviews. Selected indicators from the MUFPP and City Region Food System (CRFS) frameworks were adopted in the study.

Keywords: food system, urban farming, agroecology, urban studies

INTRODUCTION

The current data show that the main residential environment worldwide will be urban agglomerations in the near future. Inhabiting urban areas will rise up to 70% by the year 2050 (Pollalis, 2016). This fact will affect city dwellers, exposing them to negative factors such as low air quality, noise, stress, traffic congestion, inefficient urban infrastructure, anonymity, and social pathologies. Furthermore, currently, cities consume 75% of the world's primary energy capacity (United Nations Environment Programme [UNEP], 2016), emit up to 80% of global greenhouse gases, and are a source of 50% of the world's waste (Munaro, Tavares & Bragança, 2020; Dabaieh, Maguid, Abodeeb & El Mahdy, 2022). This energy consumption, greenhouse gas emissions and waste production will level up in case of anticipated urban development. Another issue is feeding the urban population. Due to increasing urbanisation, global industrial agriculture, and also climate change – fertile soils and clean water resources are shrinking. Therefore, it is highly important to protect agricultural land in and around cities. The concept within which an attempt has been made to bring food needs together with the regeneration of the environment and the democratisation of food systems is agroecology. Agroecology encompasses various approaches to solving the real challenges of agricultural production. In agroecology, the focus is on production efficiency as well as environmental and social aspects. Moreover, these aspects are taken into account on a long-term basis. This means the selection of such agrarian practices that will positively affect the environment rather than destroy it, and the appropriate (co)management of agriculture that will be

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socially inclusive rather than alienating (Simon-Rojo, 2019). The use of the term agroecology can be traced back to the 1930s, when it concerned itself mainly with crop production and conservation aspects. Currently, the term 'agroecology' denotes either a scientific discipline, an agricultural practice, or a political or social movement (Wezel et al., 2009; Fig. 1).

Agroecology is also a method for transforming food systems in a sustainable direction. It is in the agenda of the sustainable food system frameworks developed by FAO and RUAF (Food and Agriculture Organization of the United Nations [FAO], 2023) and then the Milan Urban Food Policy Pact (MUFPP, 2015). Both frameworks were developed as a tool for studying, assessing and redesigning urban (and peri-urban) food systems. The City Region Food System (CRFS) framework consists of 210 indicators – from production through to waste utilisation and food system policy and planning. The CRFS is organised around the following overarching objectives (FAO, 2023):

– Improve health and well-being and increase access to food and nutrition.
– Improve social conditions for workers.
– Build local food culture and heritage.
– Ensure acceptability of food provisions for all city residents.
– Increase local economic growth and generate a diversity of decent jobs and income.
– Strengthen the city region's food production and supply system.
– Improve protection and management of ecosystems and environmental resources.
– Improve horizontal and vertical governance and planning.
– Reduce vulnerability and increase resilience.

The MUFPP indicator framework has been developed from the longer CRFS indicator framework. It is a product of the Milan Urban Food Policy Pact (MUFPP), whose main goal is "develop sustainable food systems that are inclusive, resilient, safe and diverse, that provide healthy and affordable food to all people in a human rights-based framework, that minimise waste and conserve biodiversity while adapting to and mitigating impacts of climate change" (MUFPP, 2015). The 44 indicators of MUFPP are focused on the city and the urban food system and are organised around the six Milan Pact action categories: Governance, Sustainable Diets and Nutrition, Social and Economic Equity, Food Production, Food Supply and Distribution and Food Waste (MUFPP framework, 2023).

When it comes to food systems assessment, scholars are pointing out the key question: What a factor represents (Spence & Rinaldi, 2014; Blay-Palmer, Conaré, Meter, Battista & Johnston, 2019). Picking out one particular perspective (and following a set of indicators) will promote certain aspects and overlooks

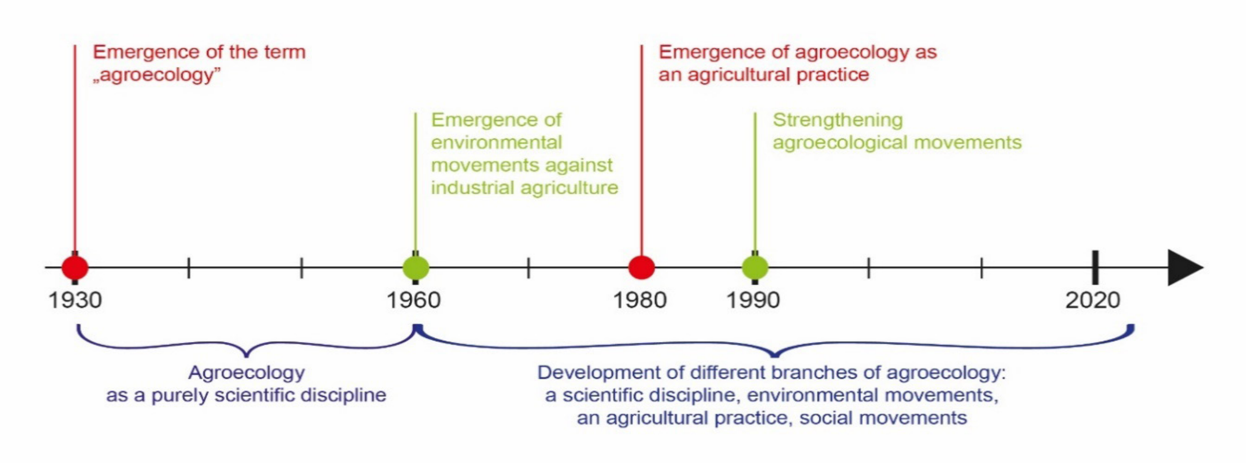

Fig. 1. Timeline presenting a development of agroecology

Source: own work based on Wezel et al. (2009).

others (Figs 2–3). Therefore, in both frameworks, sustainability was embedded in the decision-making tool. Moreover, when evaluating and designing, indicators that are the best levers for change at a particular time in a particular place should be selected (Blay-Palmer et al., 2019).

Both the MUFPP and CRFS indicator frameworks have adopted the ecosystem assessment perspective, which is more comprehensive and promotes place-specific indicators in terms of food justice, food security and food sovereignty. Therefore, in the paper herein, specific elements of these frameworks are used to discuss selected initiatives and projects in Madrid – the city, that in 2015 joined the Milan Urban Food Policy Pact (MUFPP). The goal of the paper is to review these projects and identify their potential in the context of transforming Madrid's food system into a sustainable one. The following methods were used in the study: (i) desk research – a review of academic papers and press materials provided by the various entities working on the transformation of Madrid's food system; (ii) case studies – field visits (on urban farms and in

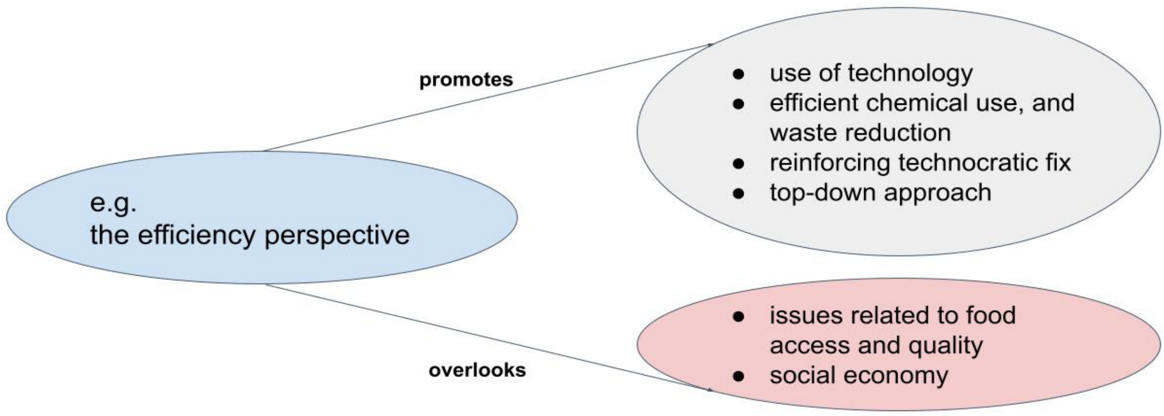

Fig. 2. The efficiency perspective on food system evaluation

Source: own work based on Blay-Palmer et al. (2019).

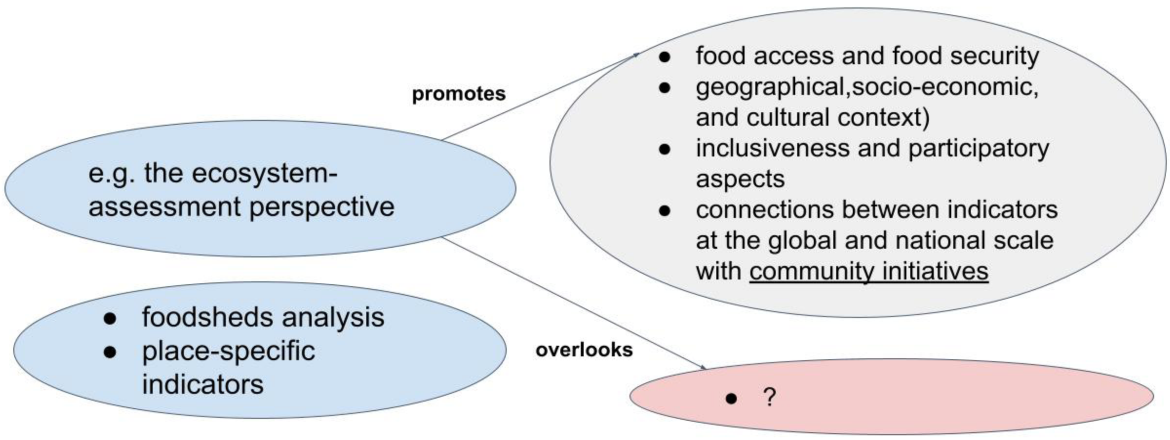

Fig. 3. The ecosystem-assessment perspective on food system evaluation

Source: own work based on Blay-Palmer et al. (2019).

community gardens, food hubs, food cooperatives as well as at farmers' markets), participatory observation (working on farms), interviews with people involved in particular food initiatives and projects in Madrid. Moreover, selected indicators from the MUFPP and CRFS frameworks were adopted in the study.

AGROECOLOGICAL PROJECTS IN MADRID

In 2015, Madrid joined the MUFPP, which is an international agreement of city mayors on sustainable food policies. The pact was preceded by many years of bottom-up organising by the food movement, also linked to the Indignados Movement (named Movimiento 15-M). The MUFPP is a declaration as well as a tool for an urban food system shift. After joining this pact, Madrid City Council developed the new Healthy and Sustainable Food Strategy 2022–2025 (EASSM 22-25), which it announced on 28 July 2022. As recommended by the Milan Urban Food Policy, the new strategy aims to foster sustainable food systems that provide access to healthy food for the city population, while supporting local green economies and local production, protecting biodiversity and reducing food waste (Ayuntamiento de Madrid, 2023). There are currently a number of grassroots initiatives for agroecology in Madrid, and a municipality project that has been insisted upon by local activists, but which is also the aftermath of the signed pact and part of the EASSM 22-25, and is gradually being implemented. The selected projects are discussed hereinafter.

Madrid Agroecologico is an initiative that brings together many organisations and informal groups working locally for agroecology. The aim of the movement is to turn a local food system transformation into a sustainable one. Since 2015, a platform has been in place to share knowledge and jointly organise the agroecology movement and it links agroecological farmers, food cooperatives and activist groups (Madrid Agroecologico, 2023). Additionally, the Madrid Agroecologico is constantly mapping agroecological projects in the region with the support of local researchers (Madrid Agroecologico Map, 2023). The area of activity of this initiative is the region of Madrid – the city and nearby agricultural land. One of their projects is Labradas Colectivas, which is a series of meetings between Madrid residents and local agroecological farmers on their farms (Fig. 4). The main goal is to help farmers – the meetings on farms were designed as a tool to carry out work which is time-consuming (especially if compared to industrial agriculture) and makes it difficult for farmers to "compete" with conventional production. During these several-hour weekend visits, city dwellers (consumers) have the opportunity to learn about agroecology, and talk and interact with farmers (producers). Integration and education take place while working together on a farm and having a meal together – a picnic after work. The work lasts about two hours and consists of simple farming activities, such as spreading natural manure. It is a barter – an exchange of agro-ecological education and rural recreation for labour: in two hours, a dozen people did a simple, but also time-consuming job that two farmers would have done for two days. A secondary goal of this project is to educate each other, as well as to create public awareness about food production. The Madrid Agroecologico initiative implements Actions 3, 7, 17–19, 25 and 33 of the MUFPP (Table 1).

Fig. 4. The Labradas Colectivas project run by the Madrid Agroecologico – a meeting between Madrid residents and local agroecological farmers on their farm called Huerta Pepines (near Madrid)

Source: photo by Aleksandra Nowysz, 2023.

Table 1. The list of MUFPP actions, which have been implemented by the initiatives discussed in the paper

No	MUFPP Category	MUFPP Action No	MUFPP Action	Initiative that implements the action
1	Governance	Action 1	Facilitate collaboration across city agencies and departments and seek alignment of policies and programmes that impact the food system across multiple sectors and administrative levels, adopting and mainstreaming a rights-based approach.	EASSM 22-25
2	Governance	Action 3	Identify, map and evaluate local initiatives and civil society food movements in order to transform best practices into relevant programmes and policies, with the support of local research or academic institutions.	Madrid Agroecologico
3	Governance	Action 4	Develop or revise urban food policies and plans and ensure allocation of appropriate resources within city administration regarding food-related policies and programmes; review, harmonise and strengthen municipal regulations; build up strategic capacities for a more sustainable, healthy and equitable food system balancing urban and rural interests.	EASSM 22-25
				Barrios Productores
4	Sustainable Diets and Nutrition	Action 7	Promote sustainable diets (healthy, safe, culturally appropriate, environmentally friendly and rights-based) through relevant education, health promotion and communication programmes, with special attention to schools, care centres, markets and the media.	EASSM 22-25
				Madrid Agroecologico
				La Osa
5	Social and economic Equity	Action 16	Promote decent employment for all, within the agricultural food sector, with the full inclusion of women.	CSA Vega De Jarama
				La Osa
6	Social and economic Equity	Action 17	Encourage and support social and solidarity economy activities, that support sustainable livelihoods in the food chain and facilitate access to safe and healthy foods.	Madrid Agroecologico
				CSA Vega De Jarama
				La Osa
7	Social and economic Equity	Action 18	Promote networks and support grassroots activities that create social inclusion and provide food to marginalised individuals.	Madrid Agroecologico
8	Social and economic Equity	Action 19	Promote participatory education, training and research in strengthening local food system action to increase social and economic equity, promote rights-based approaches, alleviate poverty and facilitate access to adequate and nutritious foods.	Madrid Agroecologico
				Barrios Productores
9	Food Production	Action 20	Promote and strengthen urban and peri-urban food production and processing based on sustainable approaches and integrate urban and peri-urban agriculture into city resilience plans.	EASSM 22-25
				Barrios Productores
10	Food Production	Action 22	Apply an ecosystem approach to guide holistic and integrated land use planning and management in collaboration with both urban and rural authorities and other natural resource managers by combining landscape features, for example with risk-minimising strategies to enhance opportunities for agroecological production, conservation of biodiversity and farmland, climate change adaptation, tourism, leisure and other ecosystem services.	Barrios Productores

Table 1 (cont.)

No	MUFPP Category	MUFPP Action No	MUFPP Action	Initiative that implements the action
11	Food Production	Action 23	Protect and enable secure access and tenure to land for sustainable food production in urban and peri-urban areas, including land for community gardeners and smallholder producers, for example through land banks or community land trusts; provide access to municipal land for local agricultural production and promote integration with land use and city development plans and programmes.	Barrios Productores
12	Food Production	Action 24	Help provide services to food producers in and around cities, including technical training and financial assistance (credit, technology, food safety, market access, etc.) to build a multigenerational and economically viable food system with inputs such as compost from food waste, grey water from post-consumer use, and energy from waste etc. while ensuring that these do not compete with human consumption.	Barrios Productores
13	Food Production	Action 25	Support short food chains, producer organisations, producer-to-consumer networks and platforms, and other market systems that integrate the social and economic infrastructure of the urban food system that links urban and rural areas. This could include civil society-led social and solidarity economy initiatives and alternative market systems.	Madrid Agroecologico
				CSA Vega De Jarama
				La Osa
				Barrios Productores
14	Food Waste	Action 33	Acknowledge the informal sector's contribution to urban food systems (in terms of food supply, job creation, promotion of local diets and environment management) and provide appropriate support and training in areas such as food safety, sustainable diets, waste prevention and management.	Madrid Agroecologico
				La Osa
				Barrios Productores

Source: own work based on MUFPP Indicator 1, MUFPP Indicator 3, MUFPP Indicator 4, MUFPP Indicator 8, MUFPP Indicator 21, MUFPP Indicator 24, MUFPP Indicator 25, MUFPP Indicator 27, MUFPP Indicator 30, MUFPP Indicator 31, MUFPP Indicator 40 (2023).

The main problem for agroecological farms is competing with large agribusiness, both in terms of selling their products and access to land. Therefore, raising public awareness of organic food production and the healthy diet associated with it is key, as this influences changes in eating habits and consumer decisions. People who are aware of the dangers of industrially produced food will be more likely to reach for locally and organically produced food. In addition to raising consumer awareness, it is important for producers to organise themselves and find alternative ways to promote and market their products. Agroecological farmers sell their products to restaurants and food cooperatives, or at farmermarkets in the city, as well as directly to consumers, such as in vegetable box schemes or the community-supported agriculture (CSA) model.

The CSA offers an alternative and unconventional exchange model that involves pre-paying for a "share" of produce, typically for a season or year, which usually takes the form of a weekly basket of vegetables (Schnell, 2013). Therefore, CSA members agree to a certain degree of unreliability and unpredictability, regarding both the quantity and quality of the food they receive. Such an arrangement reverses the conventional structure of market exchange – consumers and producers share the "risks and rewards" of food production (Watson, 2020). A situation in which consumer freedom has been replaced by a share of responsibility for the harvest may seem unattractive at first glance. However, in the long run, it is about insuring the farmer, who has the knowledge and resources to produce the food. In a circumstance where a community would lose a worker producing organic food for them (e.g., due to bankruptcy), they would also lose the products of their labour in future. Thus, the social security of the farmer is important for the entire community. Nowadays, only the farmer has relevant knowledge of food production, and in the CSA model, their knowledge, skills and work are valued. Members of the community also work a few hours a month on a farm, if possible, which is also an opportunity for them to gain knowledge and gardening skills. Such a model has been adopted in some agroecological farms near Madrid, including the CSA Vega De Jarama (Fig. 5). The farm covers an area of 3 ha, of which 1 ha is cultivated in a three-field system. Weekly 50 baskets of food are produced (about 10 kg of vegetables and fruits per basket in summer and about 3 kg in winter). Community members are also obliged to work 3–4 hours per month on the farm in the form of a Saturday duty. Nevertheless, this is also a time for spending time together and recreation. The CSA model also aims to break the alienation of work and build a community around such a fundamental thing as food. In addition, producers benefit from a guaranteed market for their products, and consumers can receive large quantities of products when the harvest is good (Watson, 2020). The CSA Vega De Jarama contribute to the implementation of the following MUFPP Actions: 16, 17 and 25 (Table 1).

Fig. 5. The CSA Vega De Jarama near Madrid

Source: photo by Aleksandra Nowysz 2022.

Another way to shorten supply chains is to establish food cooperatives. The main reasons for forming cooperatives of consumers are relatively cheap access to ethically, ecologically produced food, community building, and practising alternative economics as a counter to neoliberal economic entities focused on expanding profit. In Madrid, for example, the La Osa food co-op is thriving in the Tetuan district. In 2020, the cooperative reached several hundred members. This success precedes 10 years of creating and operating different models of shared economy enterprise in a smaller founding core group. First, it managed Consumer Group and then a small vegetable store, 2decologico. Eventually, there were enough members to turn into a co-op model and open an 800 m^2 supermarket which operates now (Fig. 6).

Currently, the cooperative has more than 1,300 members. The supermarket opened in premises owned by the municipality, which is rented on preferential terms – for an entity working for the development of the local community. La Osa is a non-profit entity – connecting local producers with consumers and creating a community around the topic of food. The main goals of La Osa are defined in the jointly developed manifesto and these are: (1) to provide its members access to quality food at affordable prices; (2) to promote and support responsible consumption as well as to promote and secure food that provides well-being to people; (3) to revitalise a relatively deprived neighbourhood in the north of the city of Madrid socially and economically; (4) to promote and practice a participatory and cooperative management model; (5) to guarantee democratic decision-making and transparency in the exercise of its tasks; (6) to include all people in their wide diversity in their community and facilitate their accessibility; (7) to take care that local farmers and producers can live with dignity from their work; (8) to commit to non-profit commercial activity and guarantee that its profits are reinvested to improve the project; (9) to follow sustainability models and implements the necessary tools and resources to reduce the environmental impact of its activities; (10) to support the transition towards a fairer agri-food system and towards food sovereignty in its territory (La Osa Manifesto, 2023).

Only members of the cooperative can shop at the supermarket. To become a member, the following is required: (1) participating for 3 hours every 4 weeks in supermarket shifts; (2) a single contribution of €100 to the share capital; (3) a 3-month trial. All members can participate in the cooperative financing, governance and operation. Decisions about the management of the cooperative are collective and each cooperative member has one vote (La Osa, 2023). Currently, about half of the members are involved in the management of the cooperative, while the rest are mainly consumers and purchase food in the store. Two people are permanently employed in the cooperative to coordinate the project, and a hired accountant handles financial issues. In addition, a special software application has been launched to support the management process. La Osa also cooperates with other cooperatives, including an energy cooperative and bicycle deliverers. La Osa co-op implements Actions 7, 16, 17, 25 and 33 of the MUFPP (Table 1).

Fig. 6. The supermarket run by La Osa co-op in Madrid

Source: photo by Aleksandra Nowysz 2022.

Agroecological projects are focused on social-ecological development, solidarity and sustainable economics. They have a real impact locally; however, being non-profit and aiming at systemic change, they face a number of difficulties in staying in business. Another association, Madrid Km 0, which was a logistics centre supporting more than 40 agroecological projects in the Madrid region, recently collapsed. Madrid Km 0 was creating coherence between the city and nearby rural food production, processing and distribution, focusing on smallholder producers and family farmers.

These types of projects should be supported in various ways by a local government. The problem is that, as economic entities, they have to be treated on an equal footing with other companies that are mainly profit-oriented and have incomparably more capital and do not necessarily have a positive impact on a local economy when socio-ecological factors are taken into account. The question remains to what extent this competition is equal. Therefore, local governments should develop a number of projects and tools to support agroecological initiatives. In Madrid, following pressure from local activists, the Urban Development Government Area of the Madrid City Council recently launched a project called Barrios Productores, which seeks to promote a green economy and employment through urban agriculture in its neighbourhoods (Barrios Productores, 2023). The project is one of the EASSM 22-25 strategy measures mentioned before.

The goal of the Barrios Productores initiative is to reclaim vacant public urban land, of which there is relatively little in Madrid, and convert it into food production sites. It is an action aimed at using land with agricultural potential in the city. The project offers substantive and legislative support in the form of consultation and professional training, as well as a plot of land for a farm through a competition. In addition, the project aims to promote the development of agricultural activities in the city, as well as healthy diets among its residents. Currently, the project is conducting a vocational course on agroecological farming (Fig. 7). The course is held at the training farm "Huerto El Pozo", and a dozen people of different ages, genders and professions are taking part. After completing the course, each participant can apply with their original projects to develop, in terms of agroecology, one of nine selected public plots assigned to host facilities or green areas, but which remain vacant. The projects have not been developed yet. These activities will contribute to the regeneration of neighbourhoods, transforming vacant or degraded spaces into multifunctional productive venues that make seasonal, healthy, local food available to neighbours through urban agriculture (Barrios Productores, 2023).

The Barrios Productores initiative is a part of, among others (including Madrid Agroecologico), an active municipal interdepartmental government body for advisory and decision-making of food policies and programmes, which indicates the following MUFPP Actions: 4, 19, 20, 22–25 and 33 (Table 1).

Fig. 7. The Barrios Productores project – the vocational course on the training farm "Huerto El Pozo" in Madrid

Source: photo by Aleksandra Nowysz 2023.

The initiatives described belong to either the private sector (CSA Vega De Jarama, La Osa) or the public sector (EASSM 22-25, Barrios Productores), as well as the so-called third sector (Madrid Agroecologico), which in this case comes from the strong agroecology movement. The public sector has received a great deal of pressure from both grassroots activists in favour of agroecology, as well as top-down pressure in the form of the MUFPP pact. From the actions outlined in this pact, the key issue is cross-sectoral cooperation between different actors. Thus, the agroecology map that Madrid Agroecologico has already been creating for years could be successfully used by Madrid City Council in implementing the current strategy (EASSM 22-25) and when planning the next ones. Moreover, the course in the Barrios Productores project, would be worth expanding and combining with work on agroecological farms already in operation, as is done at Labradas Colectivas meetings. The potential synergy of food cooperatives and farms in the CSA model also seems fruitful – such exchanges would bring urban consumers even closer to farmers.

Missing from this whole network of regional agroecology is the link that was the cooperative distribution centre – Madrid Km 0, which connected agroecological farmers with markets and organic food stores, but also with cooperatives and other less organised consumer groups. At the level of ideas, the link is the Madrid Agroecologico initiative, and at the level of policy, the EASSM 22-25 strategy. However, there is no institution, initiative or enterprise linking the various actors in the practical dimension.

CONCLUSIONS

The agroecological initiatives discussed in the paper practice entrepreneurship and local development within the green economy, which should be supported by the Madrid City Council. The development of urban farms (the Barrios Productores project) as part of a green infrastructure will help reduce the city's ecological footprint and mitigate the effects of climate change and the heat island effect, which is particularly an issue in Madrid. Supporting agro-ecological initiatives and urban agriculture is particularly important in the coming water and, consequently, food crisis, especially in Spain.

Agroecology is a comprehensive approach to food systems that takes into account both social needs and ecological constraints, as well as local context (place-specific indicators). Agroecological initiatives implement a range of actions of the MUFPP framework, which is the ecosystem-assessment perspective on food system evaluation and design. The ecosystem-assessment perspective is more useful than the efficiency perspective, which overlooks issues related to food access and quality and, likewise, the social economy.

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Authors' contributions

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

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AGROEKOLOGICZNE PRZEKSZTAŁCANIE MIEJSKICH SYSTEMÓW ŻYWNOŚCIOWYCH – PRZEGLĄD MADRYCKICH PROJEKTÓW AGROEKOLOGICZNYCH POD KĄTEM ZAŁOŻEŃ MUFPP

STRESZCZENIE

W artykule omówiono podejście agroekologiczne w transformacji miejskiego systemu żywnościowego. Przedstawiono wybrane inicjatywy i projekty realizowane w Madrycie. Celem artykułu jest dokonanie przeglądu tych projektów i określenie ich potencjału w kontekście przekształcania madryckiego systemu żywnościowego w system zrównoważony zgodnie z założeniami Milan Urban Food Policy Pact (MUFPP). W opracowaniu zastosowano następujące metody: (a) przegląd prac naukowych oraz materiałów prasowych dostarczonych przez różne podmioty działające na rzecz transformacji madryckiego systemu żywnościowego; (b) studia przypadków – wizyty terenowe, obserwacja uczestnicząca i wywiady. W opracowaniu przyjęto wybrane elementy ewaluacji MUFPP i City Region Food System (CRFS).

Słowa kluczowe: system żywnościowy, rolnictwo miejskie, agroekologia, studia miejskie

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THE IMPACT OF TRANSFORMATIONS OF THE SPACE OF TENEMENT HOUSES ON THE ARCHITECTURAL FORM OF THE BUILDING

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ABSTRACT

The study examined transformations of tenement houses carried out by development companies conducting their investments in the city of Warsaw. Tenement houses that were originally erected in the second half of the 19th century or at the beginning of the 20th century and were renovated in the last 20 years, i.e., since 2003, were examined. The research employed a combination of online resources, such as websites of development companies, architectural offices, and real estate marketplaces, to identify and gather information on renovated tenement houses. Additionally, site visits and interviews with representatives from architectural studios and development companies were conducted to supplement the collected data and gain further insights into the transformations carried out. The results of the study showed the existence of four main types of transformations that affect the architectural form of buildings: changing the function of the ground floor from residential to commercial, adaptation/reconstruction of attics for residential purposes, adding superstructures and transformations of courtyards. The impact of individual transformations on the architectural form of space is described. These changes have been illustrated with examples of Warsaw projects. The main conclusion from the conducted research is the fact that the activities of development companies that carry out their investments by renovating tenement buildings focus on increasing the area that can be sold to potential buyers.

Keywords: tenement house, modernisation, revitalisation, residential development, developer company

INTRODUCTION

With the passing of the next decades, urban, unbuilt building plots are becoming an increasingly scarce commodity. This problem is particularly visible in the largest Polish cities, especially in their city centres (Rudewicz, 2020). As a result, development companies that want to offer the purchase of housing premises located in attractive, downtown locations cannot base their activity on erecting buildings on previously undeveloped land, because there are practically no such plots in the city centres. Therefore, entities are looking for alternative solutions: demolition of existing buildings and building new ones, or transformation (modernisation, adaptation, renovation) of existing buildings.

In recent years, there has been an increase in the number of transformations of historic buildings carried out by development companies. Depending on the local conditions in each city, companies focus on different types of facilities. In Warsaw, due to the small number of post-industrial buildings that could be adapted, private entities focus on transforming residential buildings.

The aim of the article was to examine the most common space transformations introduced in tenement houses affecting their architectural form and what changes they cause. The spatial scope of the study covered the area of the capital city of Warsaw. The subjective scope includes tenement houses transformed by development companies, originally erected in the second half of the 19th century or at the

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beginning of the 20th century, and renovated in the last 20 years, i.e., since 2003.

The specified groups of transformations have been described and illustrated with examples of Warsaw implementations.

METHODS

To conduct the research, it was necessary to identify tenement houses renovated in the last 20 years and then obtain a complete set of information on the transformations carried out. Because the subject of the study was tenement houses whose transformations were initiated and carried out by private entities, no list or database is available indicating all such investments.

To identify the tenement houses being transformed and to obtain information on transformations, the following websites were used:

– development companies that specialise in the renovation of historical buildings (e.g., https://ipeco.pl, https://www.fenixgroup.pl, http://warsaw-attics.pl, https://magmillon.com),
– companies renovating historical buildings (e.g., http://www.medbud.pl, https://budizol.com.pl),
– architectural offices (e.g., http://marchwinski.com.pl, http://www.kulczynski.com),
– marketplaces (e.g., https://rynekprzedotny.pl, https://vilea.pl, https://lionsestate.pl).

The search for renovated tenement houses was also carried out using the Google Search engine, searching for results for terms such as tenement house, renovation, Warsaw, and revitalisation. The tenement houses found supplemented the list previously possessed by the author.

When examining the literature on the subject, the author did not find even a fragmentary list of renovated tenement houses, nor any holistic study describing the most typical transformations introduced by developers. The literature focuses on describing the history of individual buildings, the original architectural layout, or the analysis of individual decorative elements. The research by Jadwiga Roguska and Piotr Kilanowski should be indicated as particularly valuable in this field. Information on the transformation of individual buildings was sought by analysing the information contained on the websites of the previously mentioned entities. Photos presenting the condition of buildings before and after renovation and architectural plans and drawings were sought. To supplement the collected materials, all identified tenement houses in Warsaw were inspected. In addition, interviews were also conducted with representatives of architectural studios – studio owners and representatives of development companies – presidents of management boards and project managers. The interviews had only a supplementary function. The elements of the project were discussed, which were considered by individual persons as the most characteristic from their perspective. In total, five interviews were conducted. The information obtained allowed for a more detailed analysis of the indicated elements.

RESULTS

Roguska states that "Before the First World War, as a result of the influence of architectural and spatial mechanisms, economic factors and building regulations, a type of urban tenement house of the late 19th and early 20th centuries was formed in Warsaw, with an inner courtyard – well adapted to compact development [own transl.]." (Roguska, 2003, p. 65). The tenement house is an object rarely defined by researchers. The definitions formulated by scientists emphasise the spatial aspects of a tenement house: "a two-storey, brick town house, compactly developed, separated in terms of space and ownership and co-creating, together with the plot, the layout of a traditional urban block and street [own transl.]" (Sołtysik, 2004, p. 32) or "every multi-family, multi-storey house with a predominantly residential function, which may potentially meet the urban planning conditions of the definition (it can be encased in such a way that it forms a fragment of a building block with a front street façade and a rear courtyard façade invisible from the street) [own transl.]." (Łupienko, 2015, p. 31). These three presented definitions constitute a complete set of definitions by researchers of Polish tenement houses.

In the conducted research, a tenement house is a multi-storey residential or residential and service building with a characteristic periphery of the plot, which is or may be an element of a compact quarter development.

As a result of the query, 43 tenement houses were identified that met the study's criteria. After analysing their transformations, four main groups were identified that caused changes in the architectural form of tenement houses: changing the function of the ground floors of buildings from residential to commercial, adapting the attic for residential purposes, adding a superstructure, and transform the courtyard space. Simplified test results are presented in Table 1.

Based on the analysis of changes made in the tenement houses listed in Table 1 and literature research, the characteristics of individual transformations are presented further, including the presentation of their genesis, a description of the impact of a given transformation on the space of the tenement house and a description of related solutions. Each transformation is illustrated with an example from Warsaw.

Changing the function of the ground floors of the buildings from residential to service

Tenement houses are usually located in attractive shopping areas. The growing demand for commercial premises in downtown city districts makes adapting the space of a building adjacent to the public space of a street a natural solution (Wojtas, 1992). Such transformations were already carried out in the interwar period, in the 1930s (Ginwiłł-Piotrowski, 1931; Minorski, 1970), and they intensified in the 1980s and 1990s due to the development of private business. Changing the function of the ground floor from residential to service allows for the intensification of the street's public life by attracting new users to its space. In particularly attractive locations, the service function (commercial spaces) is also introduced on the 1st floor (Fig. 1).

The original layout of the building and subsequent transformations have a direct impact on the architectural solutions used and the scope of work necessary to carry out the work. Depending on the existing layout of the building's façade and whether commercial or residential premises were originally located on the ground floor, various transformations of the building's façade may be necessary. For buildings where the ground floor originally served service functions (Fig. 2), and the façade was not transformed in later years, the changes will have the smallest scope, focusing on the interiors. At the turn of the 19th and 20th centuries, on the main shopping streets, some shops occupied not only the ground floor but also the first floor. During the period of the Polish People's Republic, the original windows of service premises were sometimes bricked

a b

Fig. 1. Tenement house at Małachowskiego Square in Warsaw – the state before (a) and after renovation, which included shop windows installation on the 1st floor (b)

Source: [a]Hochtief (2011); [b]photo by Alicja Kozarzewska 2023.

Table 1. Transformations of Warsaw tenement houses affecting the form of space

Tenement house address	Construction period	Development investment completion date	Residential to retail change of the ground floors	Attic adaptation/ /reconstruction for residential purposes	Superstructure	Yard space transformations
Wilcza 22	late 19th cent.	2008	–	–	+	+
Mokotowska 40	late 19th cent.	2014	–	–	+	+
Hoża 50	late 19th cent.	2015	–	–	+	+
Poznańska 13	late 19th cent.	2015	–	–	+	+
Brzeska 18	late 19th cent.	2017	–	+	–	+
Środkowa 13	late 19th cent.	2017	–	–	+	+
Targowa 76	late 19th cent.	2017	–	+	–	+
Kępna 15	late 19th cent.	2018	–	–	–	+
Kopernika 15	late 19th cent.	2018	+	–	–	+
Koszykowa 47/49a	late 19th cent.	2018	+	–	+	+
Targowa 21	late 19th cent.	2018	–	–	+	+
Hoża 42	late 19th cent.	2019	–	–	+	+
Jagiellońska 36	late 19th cent.	2019	–	–	+	+
Foksal 13/15	late 19th cent.	2020	+	–	–	+
Wilcza 19	late 19th cent.	2020	+	–	+	+
Złota 83	late 19th cent.	2022	–	+	–	+
Rakowiecka 41	early 20th cent.	2005	–	–	+	+
Rakowiecka 41a	early 20th cent.	2011	–	–	+	+
Dobra 11	early 20th cent.	2012	–	–	–	+
Okólnik 11, 11a	early 20th cent.	2014	–	+	–	+
Poznańska 11	early 20th cent.	2014	–	–	+	+
Targowa 43	early 20th cent.	2014	–	–	–	+
Poznańska 16	early 20th cent.	2015	–	–	–	+
Tamka 45	early 20th cent.	2015	–	–	–	+
Wilcza 14b	early 20th cent.	2015	–	–	–	+
Okrąg 2	early 20th cent.	2016	–	–	+	+
Waliców 17	early 20th cent.	2016	–	–	–	+
Wiejska 11	early 20th cent.	2016	+	–	+	+
Górnośląska 7a	early 20th cent.	2017	–	+	–	+
Ludna 9	early 20^{-} cent.	2017	–	–	+	+
Ogrodowa 65	early 20th cent.	2017	+	–	+	+
Św. Barbary 4	early 20th cent.	2017	+	+	–	+
Jagiellońska 22	early 20th cent.	2018	–	–	–	+
Jagiellońska 27	early 20th cent.	2018	+	+	–	+
Mokotowska 45	early 20th cent.	2018	–	+	–	+
Mokotowska 52	early 20th cent.	2018	–	–	+	+
Noakowskiego 16	early 20th cent.	2018	–	–	–	+
Nowogrodzka 6a	early 20th cent.	2018	+	–	–	+
Okrzei 26	early 20th cent.	2018	–	–	+	+
Mokotowska 57	early 20th cent.	2019	–	–	–	+
Gagarina 33	early 20th cent.	2020	–	–	–	+
Łomżyńska 26	early 20th cent.	2021	–	–	+	+
Wilcza 60	early 20th cent.	2022	–	–	–	–
			The number of tenement houses given space transformation was recorded			
			9	8	20	42

Source: own work.

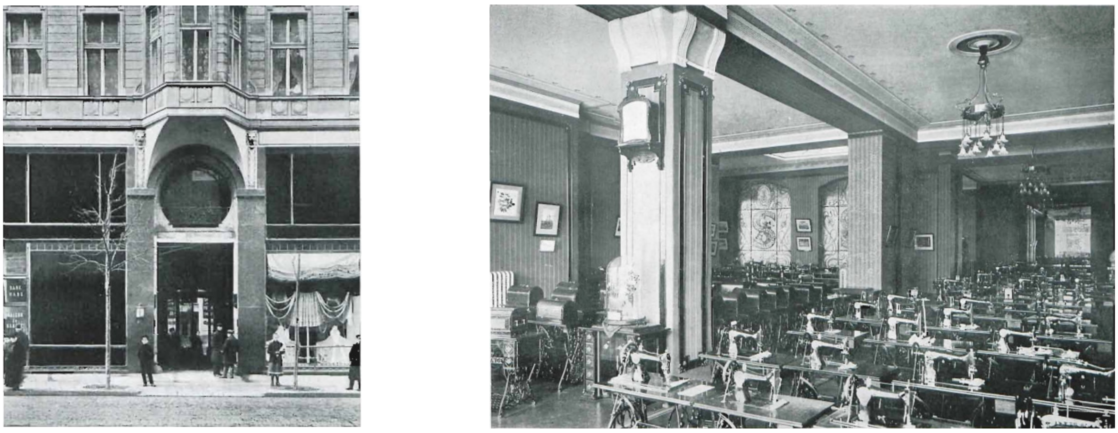

Fig. 2. The ground floor of a tenement house at Marszałkowska 137 (architect Dawid Lande) and the interior of the shop

Source: *Przegląd Techniczny* (1906), *44* (1), (tabl. XIX).

up, and residential premises were introduced in place of service premises. The new elements of the façade in the ground floor zone created in this way may differ in style from the character of the original façade. When re-adapting these premises, it will be necessary to design new façade solutions on the ground floor. The introduction of new elements on the façade will also be necessary if there was originally a dwelling on the ground floor (Fig. 3).

Possible changes to the façade include, among others: designing the entrance to the service premises, changing the dimensions of window openings, and features necessary for the operation of the service premises, e.g., a signboard. Any interference with the façade should not disturb its original composition. The need to maintain the original layout or adapt the new layout to the aesthetics of the façade on the upper floors is a significant spatial limitation: it does not always allow for adjusting the entrance to the needs of disabled people and does not always allow for a good exposure of the premises' services from the street.

Another applied solution is to merge the space of the ground floor and the first floor to obtain a high interior (an example is the transformation of Hausmann's tenement house in Paris, designed by MVRDV). A less popular solution, due to its large interference in the existing structure, is the extension of the ground floor towards the courtyard and giving it the form of an arcade (Wojtas, 1992; Fiuk, 2000). Other functional arrangements are also possible, adapted to the function introduced inside.

Fig. 3. The ground floor of a tenement house at Nowowiejska 19 in Warsaw (architect Stefan Szyller) – ground floor with a residential function

Source: *Przegląd Techniczny* (1906), *44* (1), (tabl. XXXIX).

The described conditions and the necessary transformations resulting from them can be simplified in Figure 4.

Adaptation of the attic for housing purposes

Due to the bombing of Warsaw during World War II, most of the roofs of the tenement houses were destroyed. The enormity of the damage was documented during flights over the city immediately after the war. Thanks to the photographs taken before the war, in 1935, it is possible to compare the condition of buildings before and after the war (Fig. 5).

The upper storeys of the buildings were also often damaged. Depending on the damage to a given building and the works undertaken later, different transformations of the upper parts of the building are possible. Possible solutions are shown in the diagram (Fig. 6).

Adaptation of attics is a solution – used both by communes conducting extensive revitalisation activities, private investors carrying out transformations of the entire building, as well as by housing communities transforming only the attic from the entire space of the building. Adaptation of the attic allows for obtaining a new residential space in prestigious locations, where there are no more free building plots.

The possibility of adapting the attic for residential purposes largely depends on the permissible interference in the structure and geometry of the roof and the requirement to preserve the original structural and finishing elements. Most often, the conditions for introducing a new utility function to the space of the attic are maintaining the current height of the crowning cornice in relation to the street level and the existing slope of the visible roof slope (it is possible to change the shape of the roof, e.g., viewpoint). The building where the newly built fragment of the roof has been moved back so that it is not visible from the street is a tenement house at Łomżyńska 26 in Warsaw (Bojarowicz & Żaboklicki, 2016; Fig. 7).

Due to the adjustment of the height of the attic to the new function, it will be necessary to increase the height of this storey – changing the geometry of the roof is the basic action. The sectional lowering of the ceiling of the storey below from the side of the

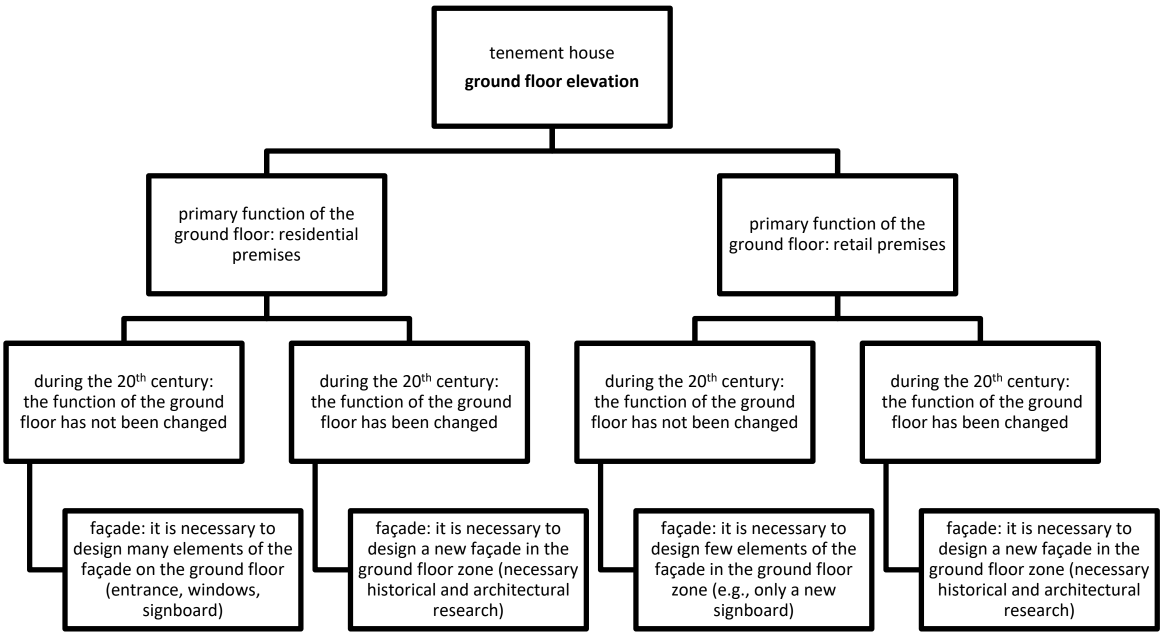

Fig. 4. Scheme of building transformations – ground floor of a tenement house

Source: own work.

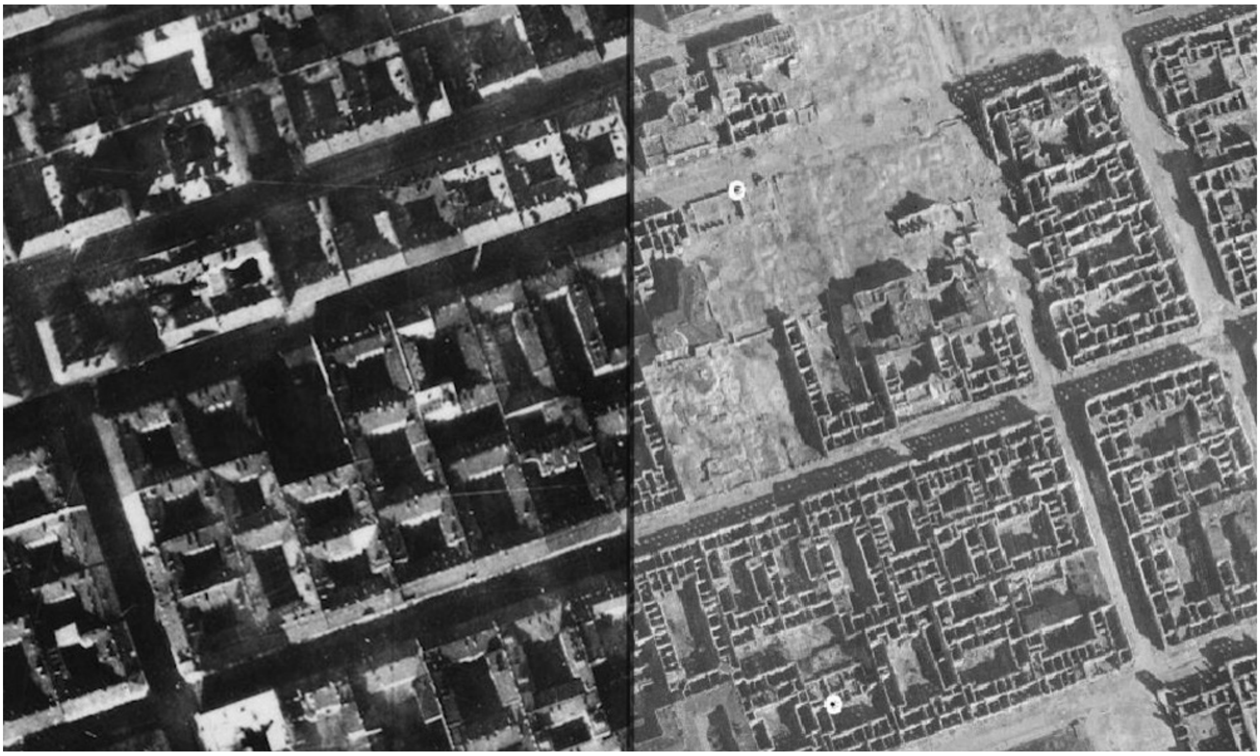

Fig. 5. Destruction of roofs in Warsaw during World War II – vicinity of the city centre

Source: Mapa.um.warszawa.pl (2022).

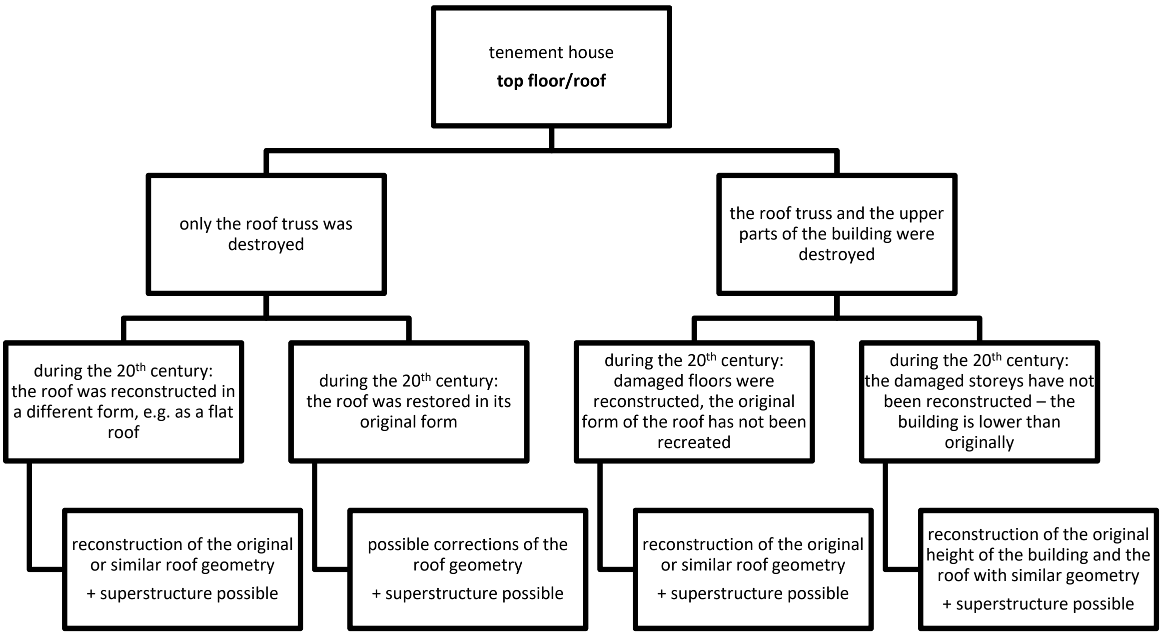

Fig. 6. Scheme of building transformations – tenement house roof

Source: own work.

a b

Fig. 7. Tenement house at Łomżyńska 26 in Warsaw – roof geometry before modernisation (a) and after modernisation (reconstruction project: architect Janusz Marchwiński). The shape of the roof, and the withdrawal of the window line, resulted from the street's visual analysis

Source: Marchwiński (2023a, 2023b).

courtyard will also allow increasing the height of the storey.

The basic issue related to the adaptation of attics is the necessary recomposition of the façade resulting from the need to widen or introduce new window openings (Fiuk, 2000; Bizio, 2002; Kilanowski, 2020). Introducing new windows (usually roof windows, knee windows or dormers) can disturb the harmony of the façade, as well as the dominant character of the cornice or roof. The spacing of new glazing will usually be related to the layout of the windows of the tenement house. Modification or addition of new windows on the front side may be limited due to the need to maintain the integrity of the façade – it is usually possible to introduce larger glazing from the courtyard side.

Importantly, Polish law does not regulate in any way what types of windows should be used. Local laws, such as local zoning plans, very rarely refer to the possible types of windows, but usually indicate the type of roof that can be used.

Superstructure

Adaptation of the attic is often associated with the addition of a new storey. The superstructure has identical conditions as the described adaptation of the attic for residential purposes. Due to the very large interference with the original substance, the superstructure should be carried out with particular care, and the superstructure of historical objects will not always be possible (Pełczyński & Tomkowicz, 2016). Superstructures that would disturb the original proportions of the building or dominate over the historical tissue should be avoided. They cause changes on two levels: the building and the urban interior. The aggressively extended building loses its original proportions. For many observers without architectural education, it is not possible to recognise what it might have looked like before the reconstruction. In addition, new loads on the structure often lead to the need to replace it, which in turn leads to irretrievable loss of part of the original substance. On the other hand, the urban interior, of which a given building is a frame, is also transformed. Its proportions and character change – it is possible to lose the perception of space as historical.

A particularly characteristic example in Warsaw of the domination of historical buildings by a modern superstructure is the transformation of a tenement house at Marszałkowska 30 (Fig. 8).

Harmonisation of the existing façade with the added volume is possible by withdrawing the new storeys, their contrasting aesthetics or continuing the style of the tenement house façade while simplifying and transforming it (Fig. 9).

a

b

Fig. 8. Tenement house at Marszałkowska 30 in Warsaw: historical form in 1910 (a) and after reconstruction in 2023 (b)

Source: [a]Kasprzycki (1999, p. 136); [b]photo by Alicja Kozarzewska 2023.

Fig. 9. The front elevation of the superstructured tenement house at Wilcza 19 in Warsaw in 2023. The façade in the strip of the top floor is stylistically different

Source: photo by Alicja Kozarzewska 2023.

Fig. 10. Renovated courtyard at Wilcza 22 in Warsaw in 2023. The courtyard has been tidied up, and a decorative floor has been introduced to emphasise the shape of the interior, small architectural objects and plants

Source: RealCo (n.d.).

Transformation of the yard space

The most common transformation of the yard space is to organise it by laying a new floor, introducing greenery (Bogdanowski, 1982; Fig. 10) or creating a playground. Spatial changes to the courtyard are limited due to its dimensions and original development. Arranging a playground will usually not be possible in tenement houses with one yard. Playgrounds are usually introduced in large revitalisation investments, where the entire quarter is transformed.

For the sake of consistency, the advantages and disadvantages of the four presented transformations are presented in Table 2.

Table 2. Advantages and disadvantages of particular types of transformations

Transformation type	Advantages	Disadvantages
Residential to retail function change of the ground floors	– Acquisition of new commercial space. – If, in the post-war period, the layout of the façade in the ground floor zone was changed, it is possible to restore the original form.	– The final effect of changing the function, the appearance of the ground floor strip on the façade, depends on the skills of the architect. – The original layout of the façade does not always allow the entrance to be adapted to the needs of disabled people. – The original layout of the façade does not always allow for a good exposure of the premises' services from the street.
Attic adaptation or reconstruction for residential purposes	– Creation of new living spaces.	– The obtained functional layouts of new apartments may be ineffective.
Superstructure	– Creation of new living spaces.	– It is possible to disturb the original appearance of the building. – Changing the proportions of the urban interior. – Significant interference with the building substance, often irreversible.
Yard space transformation	– Improvement of the aesthetics of the yard.	– Due to the small area of the yard, it is often not possible to implement elements of small architecture and playgrounds.

Source: own work.

DISCUSSION

The most frequent transformations of tenement houses described in the article, affecting their form, are a response to the changing expectations of potential buyers of apartments and the need to adapt new investments to market trends. The adaptation of the ground floors of tenement houses for service purposes and the adaptation of the attics for residential purposes contribute to the revitalisation of historic buildings, create new usable spaces and contribute to the revival of public life in the city centre. This is important for preserving cultural heritage and at the same time, adapting it to contemporary social and economic needs.

The transformations analysed in the study directly impact the architectural form of tenement houses. The adaptation of the ground floor and the introduction of commercial spaces contribute to the revitalisation of urban street landscapes and the activation of public spaces. Alterations to the attic space provide additional housing units, meeting the need for housing in densely populated urban areas. Vertical superstructures and transformations of courtyards create opportunities to expand the usable area and improve the overall functionality of the buildings.

Introducing modifications to the substance of tenement houses, in addition to the described advantages, also has disadvantages.

In particular, it should be noted that due to the destruction of buildings that took place during and after World War II, Warsaw's historical buildings are not subject to uniform protection. Whether a building is subject to any protection at all depends on the degree of its preservation. Many tenement houses are not subject to any protection, and their reconstruction, in terms of legal restrictions, is as simple as any other building. Some tenement houses are protected only by the provisions of local law – local spatial development plans, but this protection is often limited to the need to submit a construction project for inspection by the monument conservator, who may but does not have to, make comments. Only a few tenement houses are subject to full conservation protection – entry in the register of monuments.

The described legal situation means that sometimes significant interference in the original building substance is possible, resulting in irreversible loss of its original character. This happens, e.g., when replacing structural elements.

Another example of the negative impact of transformations carried out by development companies is the change of the original dimensions of the building, e.g., through a significant superstructure. This changes the pre-existing proportions of the building, making it impossible for a person with no architectural background to read the original proportions of the building.

It should also be pointed out that by changing the height of the building, the character of the public space and the proportions of the urban interior change. Changing the proportions of the urban interior should be analysed separately, but architects often overlook this element.

CONCLUSIONS

The study examined the transformations of tenement houses carried out by development companies in the city of Warsaw. The research focused on tenement houses originally built in the late 19^{th} century or early 20^{th} century, which were renovated in the past 20 years. The results of the study identified four main types of transformations that affect the architectural form of the buildings: changing the ground floor function from residential to commercial, adapting or reconstructing attics for residential purposes, adding superstructures, and transforming courtyards.

The findings revealed that changing the function of the ground floor to commercial use was a common transformation, particularly in attractive shopping areas. This transformation not only allowed for the revitalisation of the street's public life but also attracted new users to the area. In some cases, commercial functions were also introduced on the first floor.

The adaptation of attics for residential purposes was another significant transformation observed. This utilisation of previously unused space provided new residential units and contributed to the densification of urban areas. Superstructures, such as additional floors or extensions, were also implemented to expand the building's capacity and accommodate more residents.

Transformations of courtyards were identified as a means to improve the overall quality and functionality of the space. These transformations aimed to create attractive communal areas for residents.

The main conclusion from the conducted research is the fact that the activities of development companies that carry out their investments by renovating tenement buildings focus on increasing the area that can be sold to potential buyers.

Overall, the study highlighted the diverse ways in which transformations impact the architectural form of tenement houses. By understanding the factors influencing the decision-making process and the outcomes of these transformations, urban planners, architects and decision-makers can make informed decisions to shape the future development of cities and ensure the preservation of their cultural heritage.

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WPŁYW PRZEKSZTAŁCEŃ PRZESTRZENI KAMIENIC NA FORMĘ ARCHITEKTONICZNĄ BUDYNKU

STRESZCZENIE

Przedmiotem analiz były przekształcenia kamienic przeprowadzone przez firmy deweloperskie realizujące inwestycje na terenie miasta Warszawy. Badano obiekty, które wzniesiono w pierwszej połowie XIX wieku lub na początku XX wieku, a zostały odnowione w ciągu ostatnich dwudziestu lat, tj. od 2003 roku. W badaniu wykorzystano zasoby stron internetowych firm deweloperskich, biur architektonicznych i agencji nieruchomości w celu zidentyfikowania i zgromadzenia informacji o odnowionych kamienicach. Dodatkowo w celu uzyskania pełniejszego obrazu przekształceń przeprowadzono wizje terenowe i wywiady z przedstawicielami pracowni architektonicznych i firm deweloperskich. Wyniki badania wykazały istnienie czterech głównych typów przekształceń, które mają wpływ na formę architektoniczną budynków: zmiana funkcji parteru z mieszkalnej na usługową, adaptacja/przebudowa poddaszy na cele mieszkalne, nadbudowy oraz przekształcenia przestrzeni dziedzińców. Wpływ poszczególnych przekształceń na formę architektoniczną przestrzeni scharakteryzowano na przykładzie kilku warszawskich realizacji. Firmy deweloperskich realizujące inwestycje renowacji kamienic skupiają się na zwiększeniu ich powierzchni użytkowej w celu maksymalizacji zysku ze sprzedaży – to główny wniosek płynący z przeprowadzonych badań.

Słowa kluczowe: kamienica, modernizacja, rewitalizacja, zabudowa mieszkaniowa, firma deweloperska

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THE APPLICATION OF A HEXAGONAL GEOGRID AS A REINFORCEMENT ELEMENT OF THE BASE OF A ROAD EMBANKMENT

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SUMMARY

For stability calculations, one of the most important factors is the strength of the material used in the role of reinforcement. In the case of hexagonal geogrids, strength results can be obtained according to the manufacturer's recommendations – radially tensile or in accordance with the standard – using the wide-width strip specimen tensile method. It was decided to compare the strength results obtained using the radial stiffness to those resulting from tests conducted according to the standard. This article presents the utilisation of geosynthetic materials, specifically hexagonal geogrids, as reinforcement elements for soil. The article showcases the methodology and results of strength tests conducted on samples of hexagonal geogrids using the wide-width specimen method, as well as stability analysis of a representative road embankment using the aforementioned geogrid. The objective of the research was to determine the strength parameters for stability calculations of the embankment. The obtained parameters were compared with the manufacturer's specifications.

Keywords: hexagonal geogrid, tensile strength, reinforced soil, embankment, stability analysis

INTRODUCTION

The construction of embankments on weak soils often requires costly and time-consuming replacement of the subsoil or the implementation of pile or column foundations (Duszyńska & Szypulski, 2012). One solution to this problem may be the use of reinforcement at the base of the embankment, preventing excessive soil deformations and ensuring the stability of the structure (Duszyńska, 2016). Geogrids are classified as geotextile-related products (GTP) according to the PN-EN ISO 10318 standard (Polski Komitet Normalizacyjny [PKN], 2015b). The main functions of hexagonal geogrids (Fig. 1) include reinforcement of aggregate layers, steep slopes and retaining walls (Pisarczyk, 2020). In terms of reinforcement, two parameters for hexagonal geogrids are crucial: radial stiffness and isotropic stiffness coefficient.

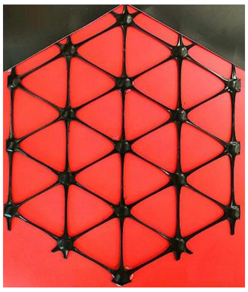

Fig. 1. Hexagonal geogrid

Source: own work.

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Radial stiffness is understood as the ratio of stress achieved at a small deformation (0.5%) and measured in all stress directions. The value of radial stiffness is the minimum value among all measured values in the range of 0–360°. This parameter determines the stiffness within the range of small, approximate deformations like those occurring under real conditions (Gołos & Woloniecki, 2013). However, the coefficient of isotropic stiffness determines the ability to achieve similar stiffness values in all directions. In the case of hexagonal geogrids, the value of this parameter ranges between 0.75 and 0.80. It can be determined based on the results of radial stiffness measurements as the ratio of the minimum and maximum stiffness, calculated from the appropriate number of measurements conducted (Gołos & Woloniecki, 2013). Additionally, the PN-EN ISO 10319 standard (PKN, 2015a) provides a testing method for determining the tensile strength of hexagonal geogrids, although it should be noted that the manufacturer does not declare the tensile strength test using this particular method.

As a result of loading, there is an ‘interlocking' effect, causing the wedging of aggregate particles within the rigid geogrid. Due to the stiff structure, lateral confinement of the aggregate particles occurs, and this effect is visible not only directly around the geogrid but also at a certain distance from it. In practice, three zones of influence (Fig. 2) of the hexagonal geogrid can be distinguished:

1. Zone of full confinement: complete interlocking of particles occurs in this zone, leading to significant wedging of the aggregate particles. Displacement is practically non-existent in this zone.
2. Intermediate zone: in this zone, the interlocking of particles gradually diminishes.
3. Unconfined zone: in this zone, the interlocking effect between particles is minimal, and the influence of particle wedging is not noticeable.

The main effects of reinforcing an unbound aggregate layer with the hexagonal geogrid are: achieving a higher density index, increasing the modulus of elasticity of the aggregate layer, enhancing the load-bearing capacity of the stabilised layer, prolonging the overall performance of the construction by extending the service life of the geogrid-reinforced layer, and providing greater resistance to deformation (Gołos, 2014). For the proper and reliable functioning of the embankment, the design of reinforcement requires adherence to the principles specified in Eurocode 7 (Duszyńska & Sikora, 2014), which are: determining the geotechnical category of the structure and its design service life, defining requirements regarding soil-water conditions and reinforcement material, specifying the construction conditions of the embankment, and conducting verification calculations considering ultimate limit state and serviceability limit state. Synthetic materials used for manufacturing reinforcement should possess appropriate strength parameters: tensile strength, chemical resistance, and be characterised by small rheological parameters (Duszyńska & Sikora, 2014). The soil material should exhibit suitable grain size distribution to facilitate easy compaction and achieve the desired mechanical and hydraulic properties. It should also demonstrate good permeability to allow water to drain from the structure and be free from chemical pollutants, with an appropriate pH value. According to the recommendations of Eurocode 7 in the case of reinforced geosynthetic road embankments, limit states are determined by checking the following events:

– overall stability loss of the terrain,
– destruction caused by surface erosion, internal erosion, or undermining,
– slope or crest failure of the embankment,
– deformations of the structure leading to loss of serviceability,

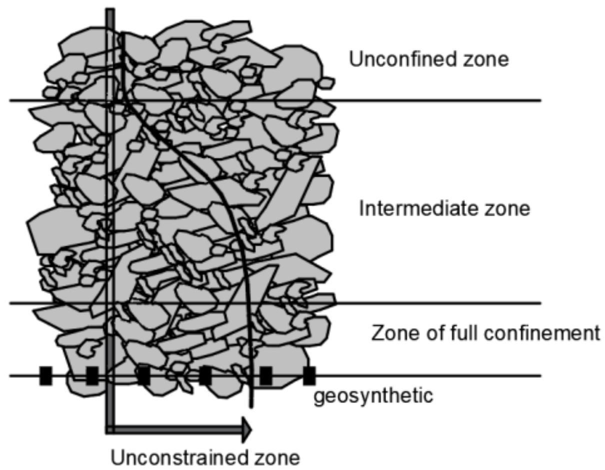

Fig. 2. Influence zones of a hexagonal geogrid

Source: own work.

– settlement and creep of the embankment affecting neighbouring structures,
– change in environmental conditions,
– high deformations in transitional zones of the embankment,
– creep of soils and road surfaces induced by temperature fluctuations,
– failure of the subgrade due to high traffic loads (EBGEO, 2011).

When performing verification calculations for the ultimate limit state and serviceability limit state, the recommendations of the EBGEO and the British standard BS 8006:2010 (British Standards Institution [BSI], 2010; Duszyńska & Szypulski, 2014) are primarily or supplementarily used. Internal stability is checked based on the assumption that a section of the structure separated by a slip line maintains equilibrium due to the strength forces of the soil and reinforcement. The calculation condition for not exceeding the limit state is generally accepted as follows:

$$E_d < R_d, \tag{1}$$

where:

E_d – the designed value of destabilising force acting on the section of the structure separated by the slip line,

R_d – the designed value limiting resistance of the embankment slope along the slip line, consisting of the resistance of the soil and the sum of the strengths of the reinforcement layers intersected by it (EBGEO, 2011).

According to the guidelines of the EBGEO, the analysis of serviceability limit states involves checking the position of the resultant force of the applied loads acting on the reinforced soil structure and analysing its displacements and deformations. The control of serviceability limit state involves considering the settlement of the subsoil, internal settlement of the backfill soil, horizontal displacements of the structure's face at different levels of the reinforcement layers, and shape deformations resulting from the deformation of the structural reinforcement (Duszyńska & Kieliszczyk, 2017).

The aim of the conducted research was to assess the behaviour of hexagonal geogrids as a reinforcement in the base of an embankment based on mechanical strength tests conducted in accordance with the PN-EN ISO10319 standard and comparisons of the results with the data provided by the manufacturer, as well as stability analysis of the slope using the GEO 5 software.

MATERIAL AND METHODS

For the strength tests using the wide-width sample method, eight samples of hexagonal geogrids were prepared by cutting them in the direction parallel to the roll axis, as well as eight samples cut perpendicularly to the roll axis. The dimensions of the samples were 200 mm in width and 200 mm in length, with a length of 100 mm between the jaws of the testing machine. The remaining part of the geogrid sample allowed for its secure attachment to the machine jaws. According to the PN-EN ISO 9862 the samples were cut from a roll, with the outer layers previously removed, to ensure that any potential manufacturing defects would not affect the test results (PKN, 2007). According to the PN-EN ISO 13251 for products intended for reinforcement, the manufacturer is obligated to provide specification of the material (PKN, 2016). Table 1 presents the specification of the tested material.

Table 1. Specification of the hexagonal geogrid used for calculations

Parameter	Value	Unit	Others
Surface mass	0.63	$kg \cdot m^{-2}$	–
Average rib length	60	mm	–
Radial stiffness	350	$kN \cdot m^{-1}$	–
Short-term tensile strength	18.91	$kN \cdot m^{-1}$	–
Raw material	–	–	PP
Type of nodes	–	–	rigid

Source: the manufacturer's data.

Embankments on weak soil foundations are often constructed using geosynthetics (Duszyńska, 2020). This allows for avoiding soil replacement and reduces the need for other more complex and labour-intensive ground reinforcement techniques. Placing geosynthetic material in the base of the embankment ensures stability during construction and enables better distribution of loads on weak soil (Alenowicz, 2009). The designed structure consists of a road embankment with a load of 25 kN·m^{-2}, a height of 5 m, a crown width of 9 m, and a base width of 31 m. The slope of the embankment is designed as 1 : 2.2. In the article, the embankment body consists of medium sand (MSa), while the base layer consists of silt clay (siCl) with fine sand (FSa) beneath it. Table 2 presents the geotechnical parameters of the soils used. Table 3 presents the technical parameters of the geotextile used for separation.

Table 2. Geotechnical parameters of soils used in the model

Type of soil	Thick-ness h [m]	Unit weight □ [kN·m^{-3}]	Internal friction angle φ' [°]	Cohesion c' [kPa]
MSa	5	19	32	0
siCL	5.5	20	15	20
FSa	6	19.5	26	0
Aggregate	0.2	20	30	10

Source: the manufacturer's data.

Table 3. Specification of the geotextile used for separation

Parameter	Value	Unit	Others
Surface mass	0.30	kg·m^{-2}	–
Tensile strength	100	kN·m^{-1}	–
Raw material	–	–	PES

Source: the manufacturer's data.

The design value of long-term strength is obtained by dividing the characteristic value by reduction coefficients and the partial material safety factor (Kiersnowska & Koda, 2018).

$$F_d = \frac{F_k}{(A_1\ A_2\ A_3\ A_4\ A_5\ A_6\ \gamma)}, \tag{2}$$

where:
F_d – long-term strength value,
F_k – short-term strength value,
A_1 – the coefficient takes into account the deformation and damage during the creep of the reinforcement; it depends on the initial reinforcement material,
A_2 – the coefficient takes into account the mechanical damage to the reinforcement during transport, placement, and compaction of the soil. It is determined based on the fraction of the soil material,
A_3 – the coefficient takes into account the influence of connections and, in the case of the EBGEO guidelines (EBGEO, 2011), seams; it is determined based on reinforcement tests comparing tensile strength over time,
A_4 – the coefficient takes into account the influence of the ground environment,
A_5 – the coefficient takes into account the influence of dynamic actions (Instytut Techniki Budowlanej [ITB], 2008; EBGEO, 2011),
A_6 – the coefficient takes into account specific conditions of foundation for structures,
γ – partial material safety factor.

In Table 4, the values of reduction coefficients for the given case according to Instytut Techniki Budowlanej requirements are presented. The strength test of the triaxial geogrid was conducted at the Strength of Materials and Structural Engineering Laboratory of the Water Center at the Warsaw University of Life Sciences (SGGW). The testing was performed according to the PN-EN ISO 10319 standard using an Instron universal testing machine with a maximum capacity of 10 kN (Fig. 3).

Table 4. Reduction coefficients

A_1	A_2	A_3	A_4	A_5
1.53	1.10	1.00	1.00	1.00

Source: the manufacturer's data.

The tensile strength (T) of the tested geotextiles was calculated using the following formula, according to the PN-EN ISO 10319 standard:

$$T = F_{\max}\, c, \tag{3}$$

where:
T – tensile strength [kN·m^{-1}],
$F_{\max}$ – maximum tensile force [kN],
$c = \frac{1}{B}$ – for geogrids,
B – nominal width of the sample [m].

Fig. 3. Instron universal testing machine

Source: own work.

RESULTS AND DISCUSSION

Tensile strength of geogrids by the wide-width specimen method

According to the PN-EN ISO 10319 standard, five specimens were tested in both directions, cut longitudinal and transverse to the roll axis. Figure 4 shows the relationship between strain and tensile strength.

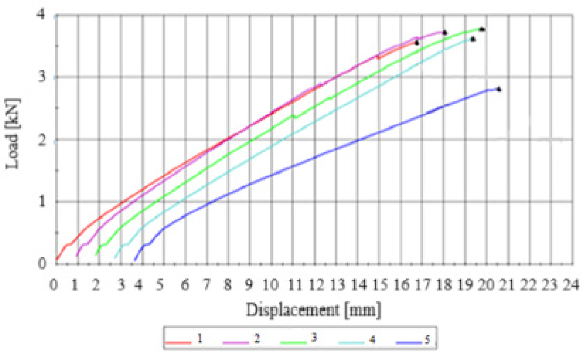

Fig. 4. The relationship between load and displacement for the specimen tested in the longitudinal direction of fabrication

Source: own work.

Based on the obtained results of the tensile strength test using the wide-width specimen method, it can be concluded that the tested hexagonal geogrid exhibits better strength properties when stretched along the roll axis. Considering the average results of the maximum force and deformations presented in Table 2, it should be observed that the hexagonal geogrid, when working along the roll axis under maximum load, can achieve a deformation that is 1.9% greater compared to the average strain value when working in the transverse direction to the roll axis. Furthermore, the average maximum load in this case reaches a value of 3.51 kN, which is nearly 131% of the maximum average value in the transverse direction. Based on the obtained results and with the use of Eq. (3), the tensile strength of 1 m of the tested geogrid was determined as five times the maximum tensile force (due to the width of the tested sample being 200 mm), resulting in T = 18.91 kN·m^{-1}. Table 5 presents the results of the tensile strength test of the hexagonal geogrid using the wide-width specimen method.

Stability analysis of a road embankment

Using the GEO 5 software, stability analysis of the unreinforced road embankment was performed. The calculated value of the stability coefficient was F = 1.42, which indicates that the permissible value of F = 1.50 was not achieved. It was concluded that reinforcement is necessary to reach the allowable value of it. In the second case, reinforcement with a hexagonal geogrid was used at the base of the embankment (specifications in Table 1). The geogrid in the program was defined individually, considering the characteristic short-term ultimate strength based on the conducted tests as T = 18.91 kN·m^{-1}, and the design long-term

Table 5. Tensile strength test results for a hexagonal geogrid using the wide-width specimen method

Direction of sample testing	Sample cut perpendicularly to roll axis			Sample cut parallel to roll axis		
	maximum load [kN]	deformation at maximum tensile force [%]	strain (standard) [%]	maximum load [kN]	deformation at maximum tensile force [%]	strain (standard) [%]
1	1.976	6.5	7.3	3.567	8.4	9.0
2	2.552	6.5	6.5	3.730	8.6	8.8
3	2.398	6.4	6.8	3.782	9.0	9.1
4	3.113	7.2	7.2	3.634	8.3	8.3
5	3.365	6.2	6.2	2.828	8.5	9.9
Average	2.681	6.6	6.8	3.510	8.5	9.0
Aberration standard	0.558	0.38968	0.47327	0.389	0.25882	0.54870

Source: own work.

strength as F_d = 11.23 kN·m^{-1} (using the reduction factors according to Table 4). The stability coefficient increased to F = 1.87, indicating that the allowable value was achieved and the specified reinforcement parameters were sufficient (Fig. 6).

In the next case, the stability of the slope was examined by using the same geogrid, but this time, an additional layer of 20 cm thick aggregate (specified in Table 2) and a geotextile (specified in Table 3) were also applied. The geotextile serves as a separation layer in the given project (Fig. 7).

The required value of the stability coefficient was obtained, which was higher than in the case without the layer of aggregate, F = 1.93. The above calculations of the hexagonal geogrid were based on its short-term characteristic strength obtained from the tensile strength test using wide specimens. The technical specification of the tested sample includes the value of radial stiffness characteristic of the triaxial geogrid. Therefore, it was decided to re-calculate the model by replacing the strength value obtained from the test with the radial stiffness value declared by the manufacturer, which is 350 kN·m^{-1}. Since the hexagonal geogrid has already been defined in the GEO 5 software, only the strength value changes, while the reduction coefficient values remain unchanged. The calculations showed that using the radial stiffness value allows the safety coefficient to be increased to F = 2.78 (Fig. 8).

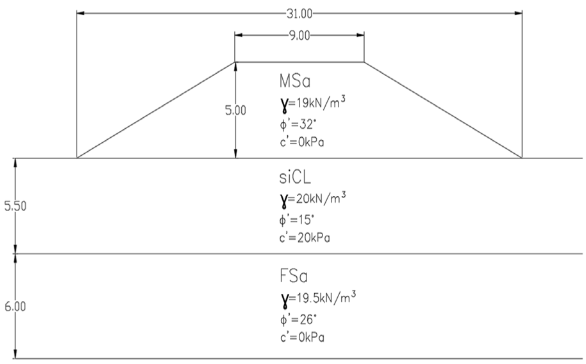

Fig. 5. Analysed cross-section

Source: own work.

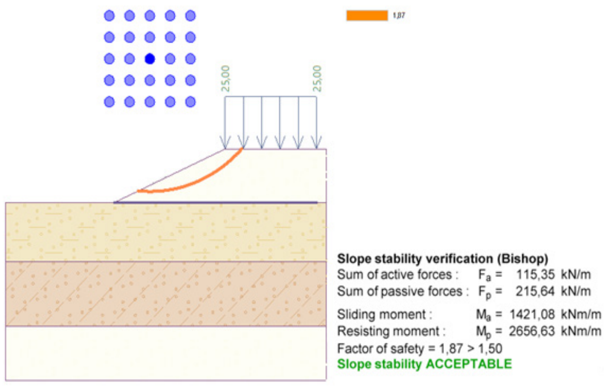

Fig. 6. Slip curve with the stability coefficient

Source: own work.

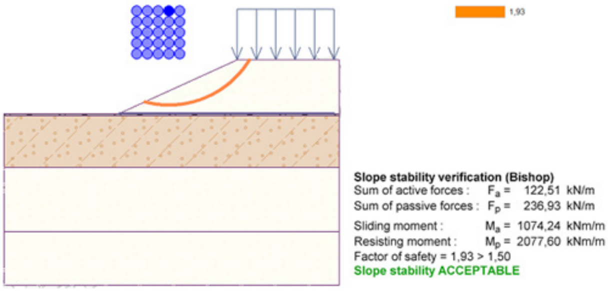

Fig. 7. Slip curve with the stability coefficient

Source: own work.

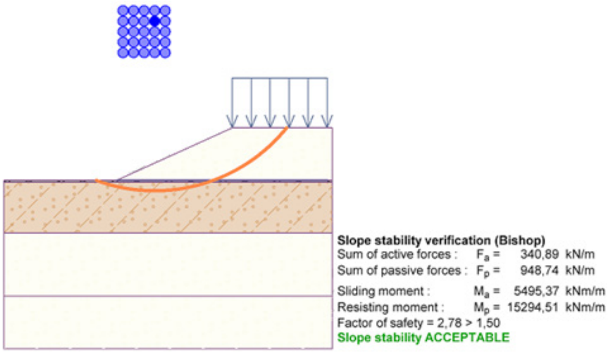

Fig. 8. Slip curve with the stability coefficient

Source: own work.

DISCUSSION AND SUMMARY

Geosynthetic materials used in road construction play an important role in the construction of earth structures. They are used in reinforcing embankments and retaining walls, allowing them to be constructed at steeper angles, even up to a right angle (Gajewska, Grzegorzewicz, Kłosiński & Rychlewski, 2003). They are also used in reinforcing the base of road embankments, preventing excessive deformation and loss of stability during the construction phase and consolidation of weak subsoil (Duszyńska, 2020).

Based on conducted research, analysis, and calculations, the influence of reinforcing the base of an embankment with a hexagonal geogrid on the stability of the structure was examined. It was found that the initial stability coefficient (obtained without reinforcement) F = 1.42 increased to the allowable (sufficient) value in each of the conducted calculations. The reinforcement with a triaxial geogrid without a gravel layer is F = 1.87, with a gravel layer is F = 1.93, and taking into account the radial stiffness, F = 2.78. In the case where gravel was used, it is presented the influence of a characteristic mechanism of action of the hexagonal geogrid – wedging. The difficulty in designing reinforcement with the investigated geogrid arises from the discrepancy between the manufacturer's recommendations and the standard regarding the testing method and determination of the strength of triaxial geogrids. Comparing the results of calculations from different studies, a significant difference in the effects of reinforcement can be observed when using strength values determined according to the standard versus the radial stiffness specified by the manufacturer. Standardising the method for examining the properties of this material would increase the design possibilities of reinforcements with hexagonal geogrids. The presented research and stability analysis demonstrate the potential use of hexagonal geogrids for reinforcing the base of an embankment. The conducted studies serve as a basis for suggesting that strength parameters should be derived from appropriate laboratory tests for specific engineering scenarios. The comparison of tensile strength results and the performed stability analysis in various cases highlight this issue, indicating discrepancies in obtained values compared to manufacturer data.

Authors' contributions

Conceptualisation: A.K. and W.S.; methodology: W.S.; validation: M.D. and W.S.; formal analysis: M.D., A.K. and F.K.; investigation: A.K.; resources: W.S.; data curation: W.S.; writing – original draft preparation: W.S. and F.K.; writing – review and editing: W.S. and A.K.; visualisation: F.K.; supervision: M.D. and A.K.

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

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ZASTOSOWANIE GEORUSZTU HEKSAGONALNEGO JAKO ELEMENTU WZMOCNIENIA PODSTAWY NASYPU DROGOWEGO

STRESZCZENIE

Znajomość wytrzymałości materiału użytego jako zbrojenie jest jedną z najważniejszych danych koniecznych do obliczeń stateczności konstrukcji. W przypadku georusztu heksagonalnego wyniki wytrzymałości można uzyskać zgodnie z zaleceniami producenta (rozciągane radialnie) lub zgodnie z normą (metodą szerokich próbek). Wyniki wytrzymałości ze sztywnością radialną postanowiono porównać do tych wynikających z badań według normy. W niniejszym artykule przedstawiono wykorzystywania materiałów geosyntetycznych (georusztów heksagonalnych) jako elementu wzmocnienia gruntu. Zaprezentowano także metodykę oraz wyniki badań wytrzymałościowych próbek georusztu trójosiowego oraz analizę stateczności przykładowego nasypu drogowego z zastosowaniem przedmiotowego georusztu. Celem badań było określenie parametrów wytrzymałościowych w aspekcie wykorzystania ich w obliczeniach stateczności nasypu. Uzyskane parametry porównano z parametrami podanymi przez producenta.

Słowa kluczowe: georuszt heksagonalny, wytrzymałość na rozciąganie, wzmocnienie gruntu, nasyp, analiza stateczności

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ORIGINAL PAPER

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RESEARCH ON THE DEGRADATION OF CONSTRUCTION AND BUILDING MATERIALS WITH THE USE OF VIBRATION PROCESSES

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ABSTRACT

Existing civil engineering structures, especially masonry structures, are subjected to heavy loads of dynamic, significant reflected vibration in the generated processes. These vibrations can affect the condition of the works by reducing the safety of people working there, as they can reach the level of endangering the safety of the structure. The effect of vibration on the structure manifests itself mainly as an additional stress, which adds to the stress of static loads. In addition, there are often the effects of climate-related environments on fatigue, which dynamize the destruction of the object. Dynamic loads can cause devastating effects in buildings of various types of construction or lead to catastrophic destruction. This article presents a modern methodology for non-invasive testing of masonry structures using vibration processes. The possibility of using modal analysis methods to assess the state of destruction elements and masonry using the process of vibration and vibration measurement is shown. This is a new approach, using innovative research methods supported by information technologies to examine the suitability of building materials and the conditions for the construction of a diagnostic agent.

Keywords: modelling, mass, stiffness, damping, vibration signal, modal analysis, stability diagram, diagnostic agent

INTRODUCTION

Great inventions, rapid growth in production, and other achievements of recent years resulted in several unintended consequences that threaten humans, the environment in which people live and work, as well as buildings. For these reasons, environmental protection of life and work is the subject of scientific interest and practical business. Matter degradation processes in the environment necessitate the need for their evaluation and the search for new study methods (Stępniewski, Uhl & Staszewski, 2013).

The construction of new materials and new technologies and inspiring design solutions enable more efficient processes but are often accompanied by high dynamic loads. There is a need to improve methods for testing the dynamic characteristics of structures, particularly those solutions that are accompanied by high dynamic loads.

In the case of dynamic loads exceeding limits, there is a need to build a model, the analysis of which can accurately identify ways and means of reducing the excessive burden. The first step in the analysis is a dynamic system identification of the vector excitation forces

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acting directly on certain elements of the structure and moving to other components, in such a way that the latter are excited to vibrate by the impact of the adjacent element. Because it is "moving up", it takes place in a selective manner, as the elements of design are the filtering properties, and it is important to know these properties (Stępniewski, Uhl & Staszewski, 2013).

Recognising the need to improve methods for testing the quality of masonry building structures to assess their condition and assess the safety factors of walls (PN-B-03002, pts 3.1.3 and 4.6), this paper attempts to develop a methodology for testing the quality of selected materials and the destruction of building structures using the modal analysis method (Allemang & Phillips, 2004).

Occupying an important place in this regard is the frequently-used non-destructive testing of masonry in the laboratory, as well as studies directly on the structure using the sclerometer methods (fingerprint measurement method, the method of measuring the rebound), pulse methods (ultrasonic, hammering), radiological methods (radiographic, radiometric), electromagnetic methods (magnetic, dielectric) and special methods (e.g. electrical methods).

Both the mentioned dynamic research systems and experiments are performed on the real objects (Cempel, 1994).

New tools in this area of research relate to the possibility of using modal analysis methods, as well as modern mining and vibration processes, to assess the quality of construction and masonry, which form the basis of considerations of this work. In practical applications, they allow for a better understanding of the behaviour of complex structures in the process of optimising the design and evaluation of dangerous conditions (Cempel, 2003).

Modal analysis is widely used in studies of degradation status and fault location, in the modification of the dynamics of these structures, in the description and updates of the analytical model, and is used to monitor the vibration of structures in the aerospace and civil engineering fields (Żółtowski, 2014).

The study recognises the usefulness of modal analysis methods to evaluate the degradation in the quality of materials and structures, and proposes a research methodology for acquisition, processing and reasoning for the data obtained in the study on building degradation.

MATERIAL AND METHODS

Experiments that identify the failure state of the test masonry are the primary source of information, and from the measurements, the structure of the model can be determined. On the one hand, the quality of the experimental results obtained depends on the quality of the model, and on the other hand, the manner of experimentation determines the structure of the identified model.

Modal analysis experiments can be divided into the following steps:

1. Experimental plan:
   - selection of the type of vibration load on the test piece and the point of application,
   - selection of measuring points and vibration measuring devices,
   - selection of suitable measuring equipment,
   - selection of the system model (reduction in the number of degrees of freedom).
2. Calibration of the measuring path.
3. Record and process test results.

The purpose of this experiment is to perform a modal analysis of the motion of a masonry sample by energising and measuring the response to the blackout. Based on measurements of the vibration process, the properties of the examined masonry can be estimated. The general process for carrying out this work is shown in Figure 1.

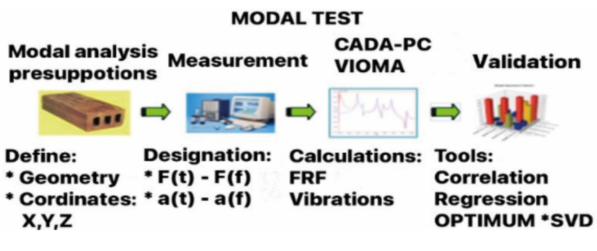

Fig. 1. The essence of the measurement channel using modal analysis

Source: own work.

The force conversion signal applied to the sample corresponds to the vibration signal, proportional to the failure state. The applied force and response signals are used to determine the function of the further FRF, the stability of the graph, as well as the oscillation frequency. Additionally, with these methods, the vibration estimator can be used for other interesting cognitive processes, which can also be used for further research. The test results are processed by various algorithms for statistical analysis. From the point of view of experimental modal analysis, methods can be divided into:

- a method to force the movement of multiple actuators to excite a waveform,
- a method of forcing one or more points to move and measure the transfer function.

The first group of methods is to manually move the system to force the vibration according to the vibrating embodiment. This requires a complex control system of the actuator to obtain the proper phasing force. The second group is used to enforce any action based on the object type. The complete set of equipment for the modal analysis experiment consists of the following parts:

- dynamic and reaction force measurements,
- signal conditioning system (preprocessing),
- processing and collection of signals,
- forced signal generation system,
- vibration excitation.

For maintenance reasons, the simplest solution is to use a signal analyser, but the most modern solutions with the greatest potential are based on workstations and special interface measurements. The basic operation performed by all applicable devices measuring modal analysis is analogue to digital processing, which enables the use of digital signal processing techniques to determine the modal analysis required by the characteristics of estimators.

Modal studies do not consider the magnitude of motion in which the system responds. In fact, displacement measurements give better results in terms of accelerations in the low and high frequency ranges. It is generally accepted that velocity measurements are optimal for structural dynamics studies because the root mean square vibration velocity is, in a sense, a measure of the kinetic energy of the system's vibration. However, sensors for displacement and velocity measurement are relatively heavy and affect the behaviour of the test object, while acceleration sensors are much smaller and, therefore, have no effect on the motion of the system. Another advantage of accelerometers is that the velocity or displacement oscillations can be integrated to obtain another signal from the acceleration signal. The reverse operation consisting of differentiation can lead to large errors, especially at higher frequencies.

On those grounds, acceleration sensors are the most used transducers for studies of modal structure. Acceleration sensors built on the piezo-electric phenomena can be modelled as a system with one degree of freedom from suppression. The weight of this model is the seismic mass aggravating crystal piezoelectric material during movement. Due to the design of the sensors, it has a resonance, which reduces the frequency range in which they can be applied (Żółtowski & Żółtowski, 2014).

Measuring software

Registering of vibration signals (excitation and response) in tested masonry elements is quite complicated, but vital to determine the state of destruction (Żółtowski i Martinod, 2016).

Determination of modal parameters is done with the stabilisation diagram, which can be obtained directly from the numerical modal analysis (LMS) or using the least squares complex exponential method (LSCE). It has been implemented in the "VIOMA" used to carry out an initial operational modal analysis (Stępniewski et al., 2013). The program consists of the following modules:

- "Data" module – used for downloading, viewing, and simple measurement data processing,
- "Geometry" module – allows the building and visualisation of the object's geometry,
- "Analysis" module – implements modal analysis, including the LSCE method,
- "Visualisation" module – allows visualisation of analysis results.

Figure 2 shows an example of a stability diagram, where the stable poles were selected from the 39 for the following estimation of the normal modes. The data obtained as a result of the analysis can be represented graphically via the "Visualisation". Figure 3 shows samples with selected natural frequencies.

Measured waveforms generated by force and response of the measured samples, and the possibility of determining the modal parameters of the model in the study of masonry structures can be made by measuring equipment named LMSTEST.XPRESS LMS (Fig. 4).

The LMS software allows for the creation of a diagram of one stabilisation measurement (option "Selected function"), and it is possible to create a stabilisation diagram for all measurements (the "SUM"). The sample stabilisation diagram is shown in Figure 4,

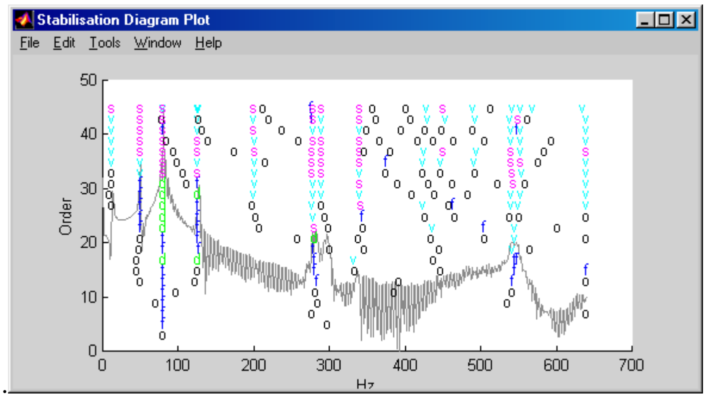

Fig. 2. Stability diagram and method for determining the poles: o – unstable pole, f – pole has a fixed frequency, v – pole has a fixed frequency and a modal vector, p – stable pole

Source: own work.

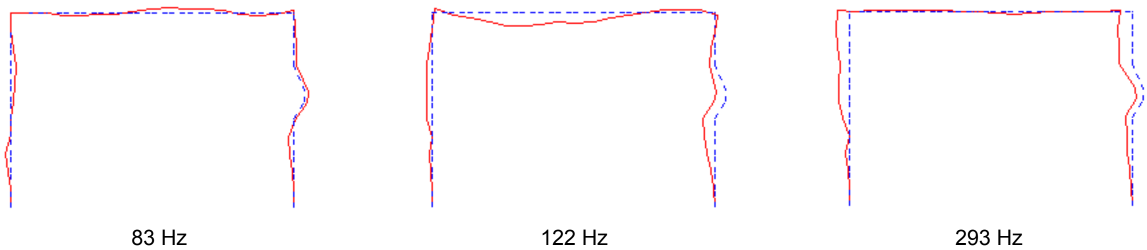

Fig. 3. Sample forms for the selected natural frequencies

Source: own work.

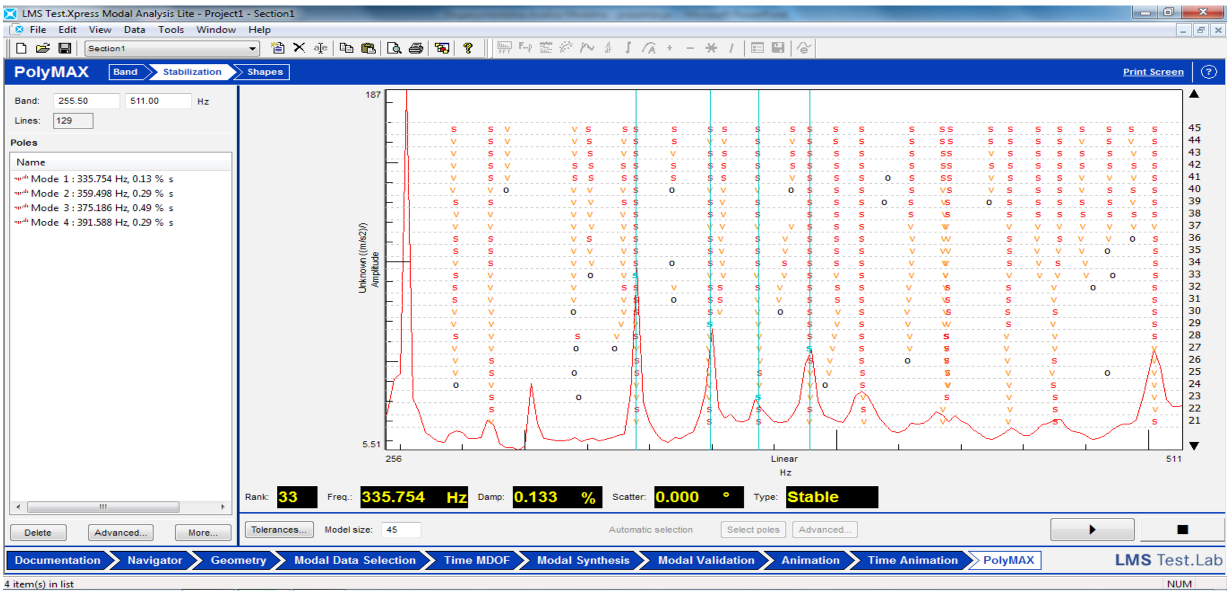

Fig. 4. The stabilisation diagram

Source: own work.

which introduces the polarity markings: S – stable, V – modal vector, and D – damping. The software option "Mode" is suitable for the visualisation of a geometric deformation model.

The software (accurate, durable and reliable) allows for the implementation of a variety of experiments, often in difficult and not very reproducible conditions.

Compilation of statistical results

Many measurement data processing capabilities resulting from vibration signals lead directly to the need for statistical analysis.

In practical applications, preconditioning obtained from the measured data is an important step in the data classification, affecting both the efficiency of distinguishing between states, the speed and ease of construction and the learning model of cause-effect as well as its subsequent generalisation (Wiliams, Crowley & Vold, 1985).

Analysing the experimental data is associated with the occurrence of various kinds of scales of measurement, which may be numerical or symbolic. Diagnostic information processing systems are characterised by the fact that the most frequently analysed features describing the objects should be characterised numerically.

In the case of classification models using the distance as a measure of similarity, it often happens that the various features are characterised by a physical state based on various physical quantities having different ranges of values, which can have different effects on the distance. Here, it is possible to apply several transformations, unifying the influence of individual characteristics on the distance value. The most common is the normalisation and standardisation.

Optimum

Optimisation techniques may be based on measurements of the distance from the ideal point measured to characterise the sensitivity to changes in symptoms. The distinction of damage is possible after symptoms of components projected on the respective axes x, y, and z (Fig. 5).

The presented algorithm allows the development of a statistical evaluation of diagnostic symptoms, resulting in a final ranking list of their sensitivity and usefulness. The next step of this procedure is (Żółtowski, Łukasiewicz & Kałaczyński, 2012):

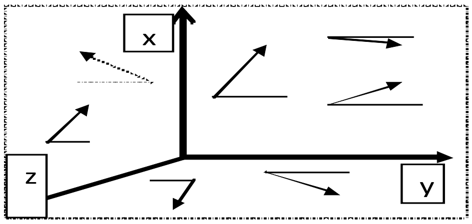

Fig. 5. Multidimensional observation space

Source: own work.

1. Creation of an observation matrix from the measured symptoms: $s_1, s_2, s_3, ..., s_m$.
2. Statistical evaluation of symptoms measured for different states by means of, for example:
   – variability of symptoms:

$$f_1 = \frac{S_j}{\vec{y}}, \tag{1}$$

where:
S_j – standard deviation,
$\vec{y}$ – the average;
   – assessment of symptom sensitivity to changes in:

$$w_1 = \frac{x_{i\max} - x_{i\min}}{\overline{x}_i}; \tag{2}$$

   – symptoms correlate with technical condition (correlation coefficient symptom – state):

$$r_{xy} = \frac{1}{n-1} \frac{\sum_{i=1}^{n} \left(x_i - x_{\text{avg}}\right)\left(y_i - y_{\text{avg}}\right)}{\sigma_x \sigma_y}.$$

$$f_2 = r(x, y). \tag{3}$$

3. When standardisation further maximises signal quality, measurement indicators obtain statistical characteristics of their sensitivity, which allows the determination of the coordinates of the ideal.
4. Determination of the distance measurement from the ideal point, according to:

$$L = \sqrt{(1 - f_1^*)^2 + (1 - f_2^*)^2}. \tag{4}$$

5. The sensitivity coefficients (weights) for each test signal are determined from the relationship:

$$w_i = \frac{1}{\frac{1}{L_i} \cdot \sum_{i=1}^{n} L_i}, \text{ where } \sum w_i = 1. \tag{5}$$

The algorithm can easily be implemented in MS Excel to give a qualitative ranking of the usefulness of the measured symptoms. Figure 6 shows the result of the described action procedures for sample data. The distance of each measurement point from the ideal point (1, 1) indicates the sensitivity of the evaluated measurement signal, and the points lying closest to (1, 1) are the best symptoms.

The quality of the model depends, however, on the number of measures considered, which indirectly, in the simplest regression models, can be assessed by the coefficient of determination (R^2).

Research methodology of masonry units

To test the usefulness of experimental modal analysis and assessment of the severity of the destruction of masonry and building materials using the vibration signal for selected representatives of the groups (EC6V):

– ceramic elements (EN 771-1) – solid brick, hollow brick, porotherm,
– elements of silicate (EN 771-2) – aerated concrete (suporex),
– concrete elements (EN 771-3) – cube (brick), concrete, concrete block.

Figure 7 shows a sample set of research material, before the destruction of the basic research.

The first bench testing was performed for unloaded masonry, with the release of test items for many degrees of freedom, which was obtained by suspending the items on an inextensible thread (Fig. 8).

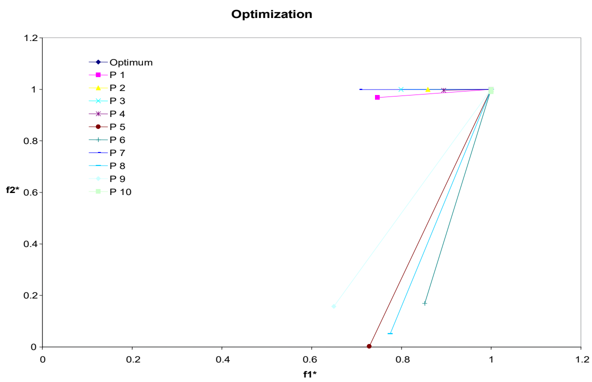

Fig. 6. The result of the ideal point method – OPTIMUM

Source: own work.

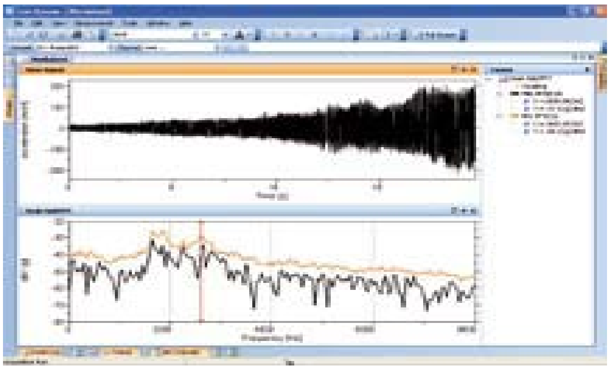

Fig. 7. Masonry and masonry segments adopted for testing

Source: own work.

Fig. 8. Attaching the sample, sensors, and test stand

Source: own work.

Measurements of vibration signal parameters (Fig. 9) were performed using a measuring package – the APB-200 processor that is part of CADA-PC software.

Fig. 9. Schematic structure of a measuring program

Source: own work.

In practice, the study was carried out with no load and with a load testing machine (Fig. 10). Tested vibratory signals are dependent on the type of load of masonry, which results from the nature of the load curves obtained during a destructive test testing machine for each piece of masonry.

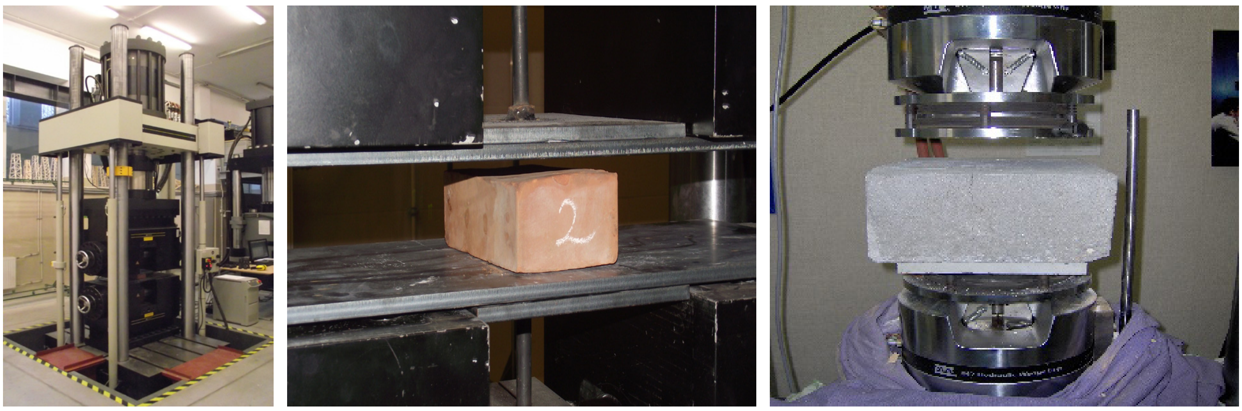

Fig. 10. Test under load testing machine

Source: own work.

RESULTS AND DISCUSSION

The results of destructive testing of selected masonry on the machine Instron 8502 are shown in Figure 11, and they were the basis for determining the load of test materials and masonry.

Deliberately, tensile test results are summarised in Figure 11, and they are in the range of:

– for items marked as 2, 4, 5 – load testing: 25 kN, 50 kN, 75 kN,
– for items marked as 1, 3, 6 – load testing: 50 kN, 100 kN, 150 kN.

In further studies, each element of walled compounds was tested between the types of measures (indicated above 3, and no load) and the vibration signal generated. Experiments carried out to verify the suit-

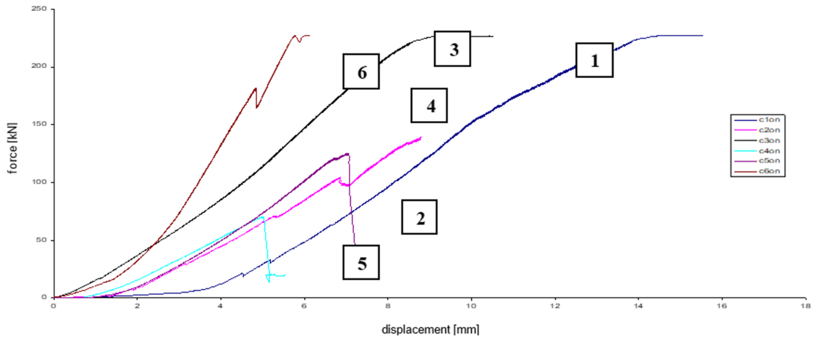

Fig. 11. Time passes to the destruction of the load curves for the tested masonry units: 1 – solid brick; 2 – hollow brick; 3 – concrete blocks; 4 – suporex; 5 – porotherm; 6 – concrete block

Source: own work.

ability of the FRF measurement of vibration and other estimators to assess changes in the destruction of some masonry gave almost 3,500 different measurements of vibration (vibration estimators studied 12 × 6 × 2 masonry directions of load measurements × 4 equal to 576 measurement values; and a further 576 measurements × 6 sets of masonry equal to 3,456 vibration signal measurements). Exemplification earned on this data research methodology is the next big data group and underwent the same procedure processing.

Archived timing and strength of vibration acceleration force (1,024 samples) measured along the X and Y for different loads of studied masonry form the basis for further processing. From the raw data presented in MS Excel sheets using the software GENERATE symptoms, made in MATLAB for the purposes of this research, generated 12 representative measurements of the state for each tested masonry elements.

Graphical presentation of the data in the MS Excel tables presented in the form of amplitude characteristics in the X and Y axes are shown in Figure 12.

In Figures 13–15, power waveforms are shown in the form of modal hammer force and the corresponding amplitude of vibration acceleration for the tested masonry materials with different loads F_1, F_2 and F_3. It is worth noting that the first group of materials – solid brick, concrete brick, and concrete block, are loaded at the time of testing forces: 50 kN, 100 kN and 150 kN. The second group materials – hollow brick, porotherm and suporex forces during the tests: 25 kN, 50 kN and 75 kN.

Timing and response force, shown in Figures 13–15, do not allow for any reasonable inference, but illustrate the data used in further analyses.

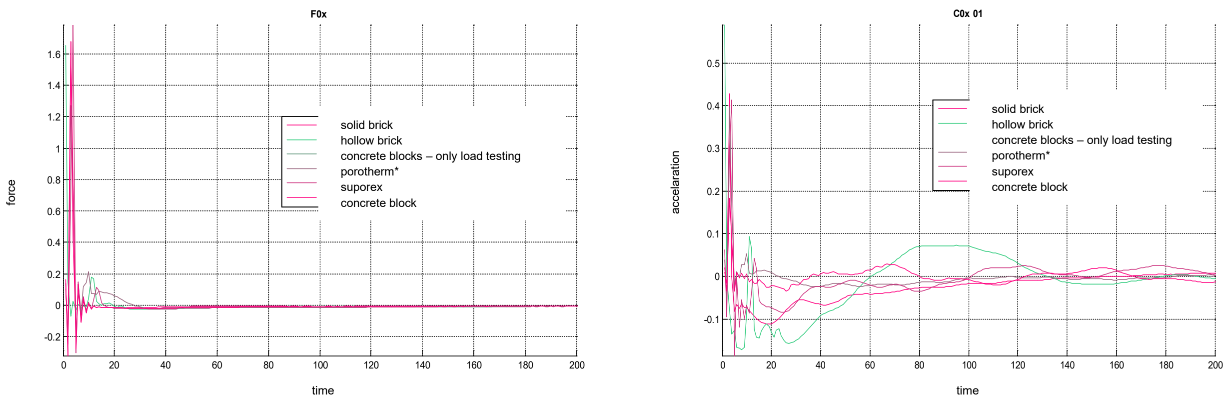

Fig. 12. Force and amplitude of the vibration acceleration along the X-axis for the test of six masonry elements without the F_{0X} load

Source: own work.

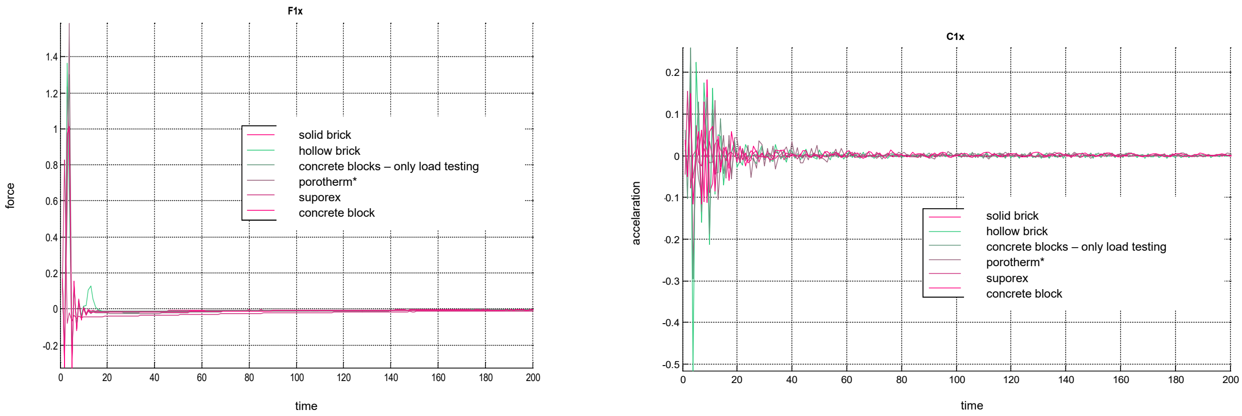

Fig. 13. Force and amplitude of the vibration acceleration for the test of six masonry elements with the F_{1X} load

Source: own work.

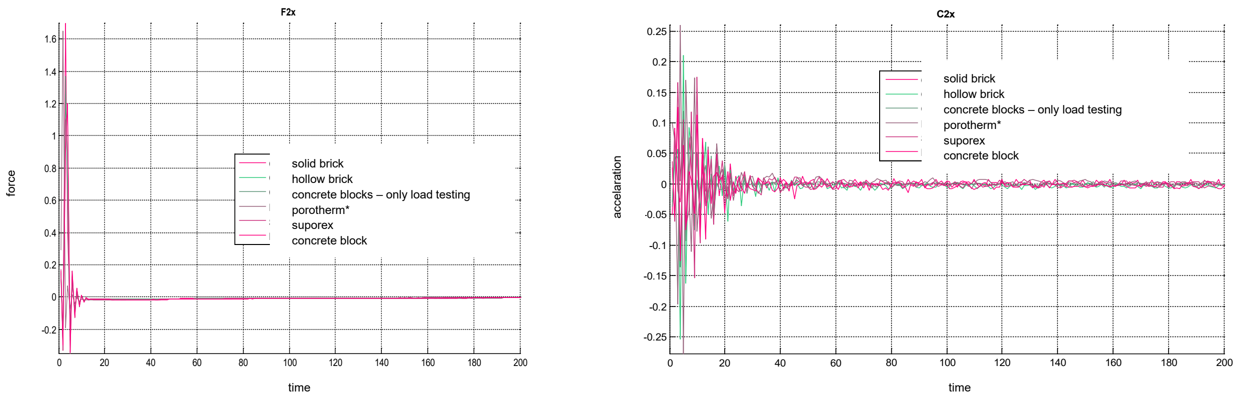

Fig. 14. Force and amplitude of the vibration acceleration for the test of six masonry elements with the F_{2X} load

Source: own work.

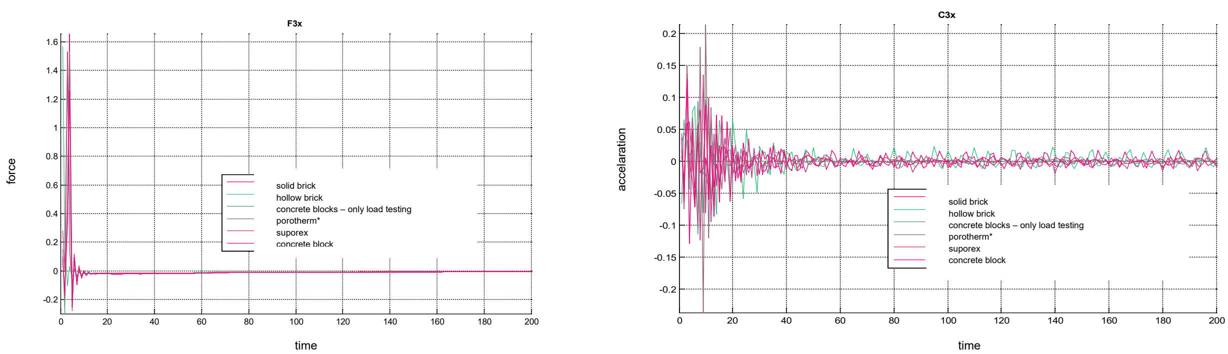

Fig. 15. Force and amplitude of the vibration acceleration for the test of six masonry elements with the F_{3X} load

Source: own work.

Figures 14 to 16 show the measure of destruction state for full brick that has been tested with no load and fixed earlier in the strength tests with three load values for only the original signal strength X. Force and acceleration amplitude of response function FRF was converted to spectral domain (frequency). Figure 16 shows the waveforms and their spectra for excitation force and the response to research full brick in the X direction.

The ratio of power spectrum amplitude and spectrum force vibration acceleration determines the function of the FRF (real and imaginary). Inversion of the FRF is a widely known transmittance function (real and imaginary). Changes in these measures on the frequency scale are shown in Figure 17.

Indicated earlier measurement – coherence function, with a good examination of the similarity between two signals in the frequency domain, and the cross-correlation function, with similar properties, but are defined in the time domain, are shown in Figure 18.

Figure 19 shows the waveform of an effective overall amplitude vibration and stability diagram obtained from the VIOMA program and characteristic eigenfrequencies of studied masonry elements.

The same measurements were obtained in studies of the workload for different values of all the tested masonry – the numerical values of measurement signals for each masonry with different levels of power load, and the input data for the development of statistical results. To distinguish the best measures for the

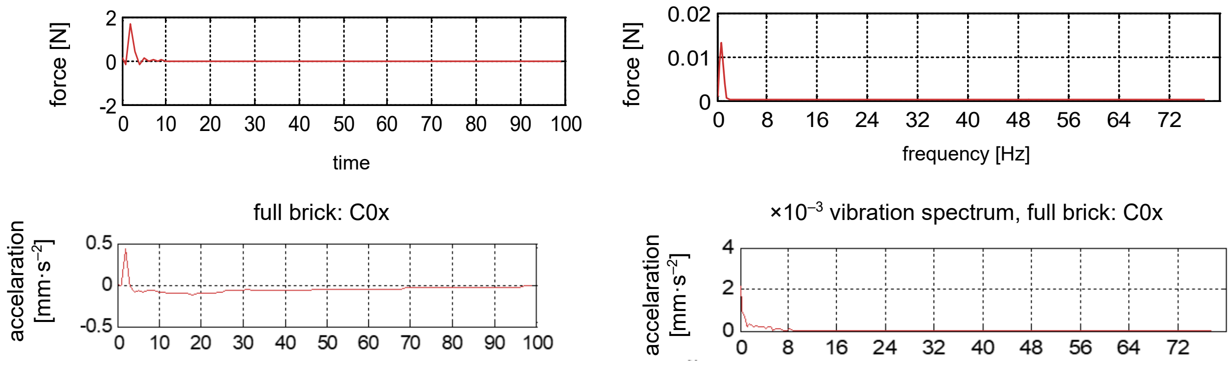

Fig. 16. Timing and power spectrum for the acceleration force and amplitude of the test response with no load

Source: own work.

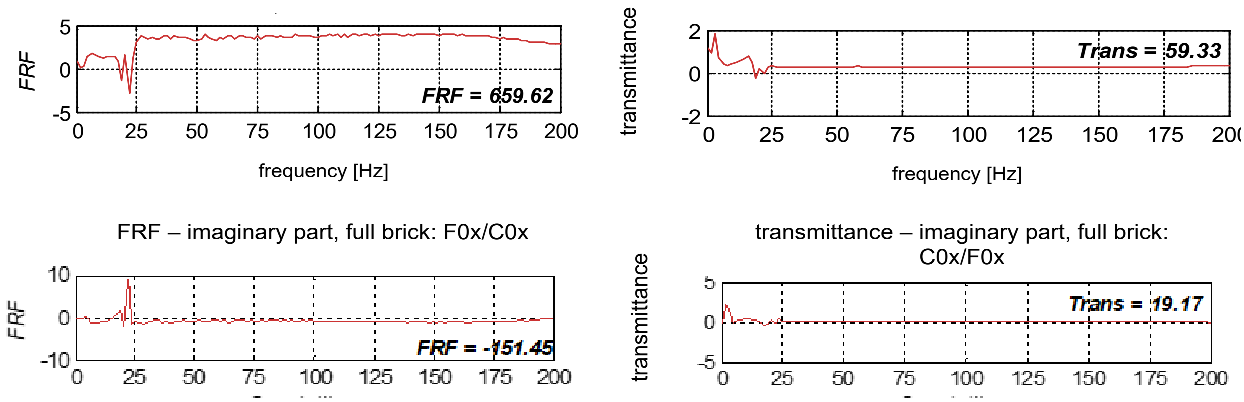

Fig. 17. The FRF variation waveforms and *H*(*f*) (real and imaginary parts) of the test without load

Source: own work.

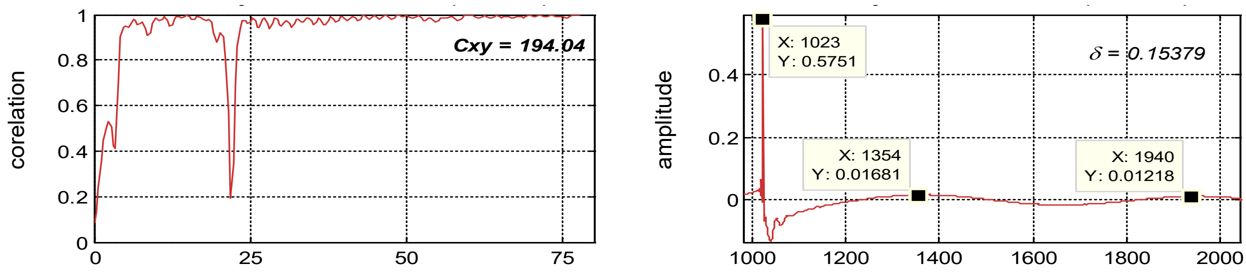

Fig. 18. The waveforms of the coherence function and cross-correlation function

Source: own work.

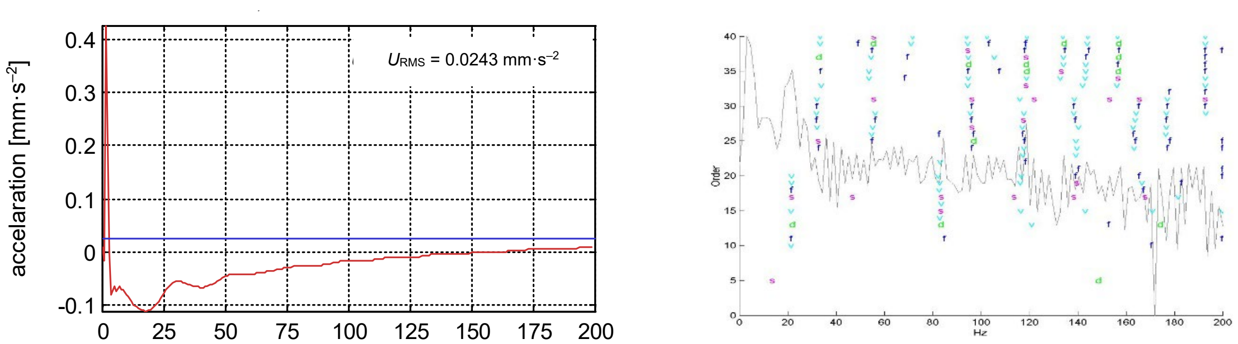

Fig. 19. Waveform amplitude and vibration acceleration effective stabilisation diagram with characteristic vibration frequencies

Source: own work.

destruction of the state of the tested masonry results were subjected to statistical evaluation first by the OPTIMUM method. Figure 20 illustrates cumulative sensitivity results of the measurement of destruction symptoms separately for the X-axis and the Y-axis.

Measures located closest to the ideal point of destruction best reflect the behaviour of masonry investigated under increasing load. A careful analysis measures the distance from the ideal point shown in the graphic display of all analyses treated individually as

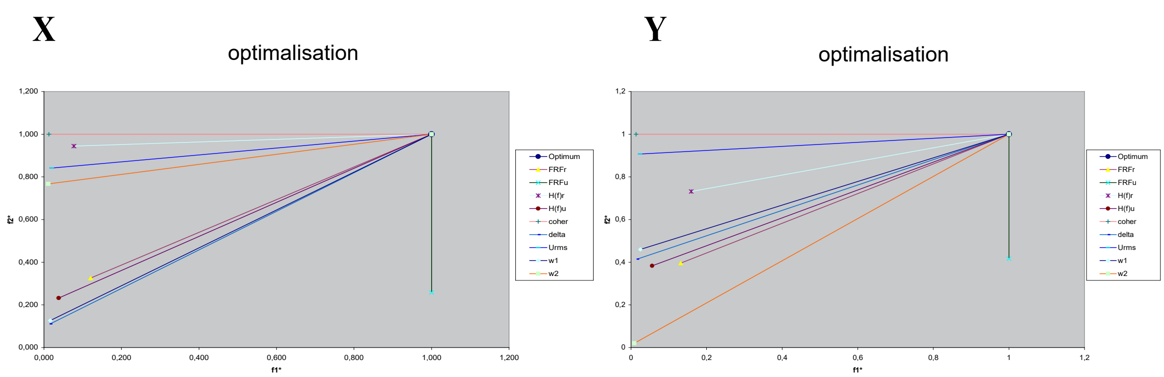

Fig. 20. Collective results of the sensitivity of the destruction of masonry elements

Source: own work.

a result of the two criteria (1 and 2) and permits the following ranking of the sensitivity of the tested measures:

– the direction of the axis X: FRF_u, $H(f)_r$, FRF_r, U_{RMS}, *coher*, ω_2, $H(f)_u$, ω_1, δ,

– the direction of the axis Y: FRF_u, $H(f)_r$, FRF_r, $H(f)_u$, U_{RMS}, *coher*, ω_1, δ, ω_2.

The tested destruction of masonry elements differs slightly in sensitivity factors and distance at each stage of the procedure, which makes conclusions difficult, although it allows preliminary confirmation of good properties in the following ranking:

FRFr FRFu H(f)r H(f)u URMS coher ω2 ω1 δ

Quantitative studies of the compounds described above and measurements of the state of the reflected load destruction applied were carried out using linear regression tests (simple and multiple).

Figure 21 shows the test results of multiple linear regressions, binding on all the relevant mathematical formulas, for study of destruction in masonry structures (full brick and suporex) depending on the load.

coefficient (R^2), also known as the coefficient of determination, the host value in the range [0, 1]. Its value is given in the regression figures, where the higher the value, the better the correlation – a better fit to the regression results.

The following is a summary table (Table 1) of the frequency of vibrations generated for the measurement of the various states of degradation of the existing brick structure.

Table 1. Summary of natural frequencies for the different states of degradation of the structure

Extortion	Fit wall element	1 crack	2 cracks
No force	71,388 Hz	39,999 Hz	29,831 Hz
No force	81,699 Hz	40,806 Hz	39,207 Hz
With force	43,526 Hz	41,271 Hz	70,844 Hz
With force	81,699 Hz	147,588 Hz	110,296 Hz

Source: own work.

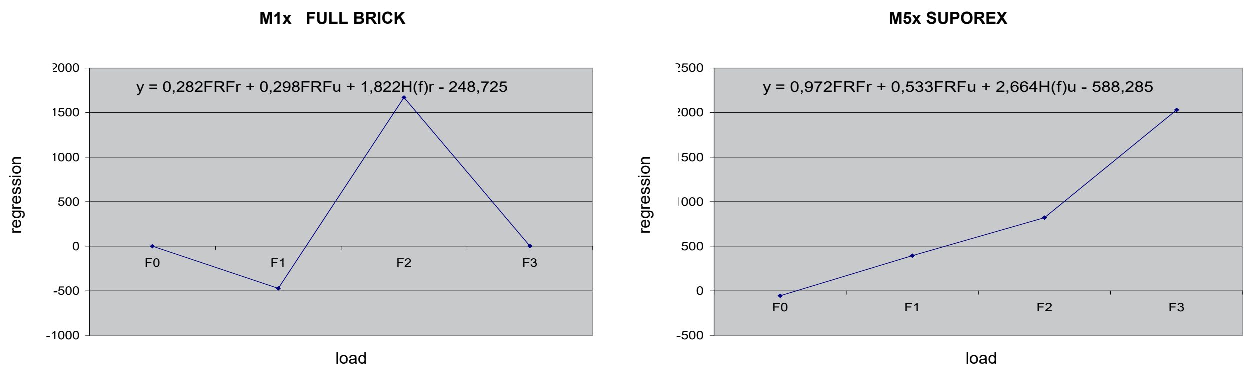

Fig. 21. Multiple regression results for all measures and examined loads

Source: own work.

The entire procedure consisted in determining the good state of damage to the tested masonry elements and establishing a cause-and-effect relationship between the condition and the destruction of the components. Approximation error of studied measurement functions was determined as multivariate correlation

Qualitative results without damaging the brick wall and damaged walls conducted by operational modal analysis (ODE) are presented in Figure 22.

A comprehensive of natural frequencies of studied states of brick wall degradation using experimental and operational modal analysis are shown in Table 2.

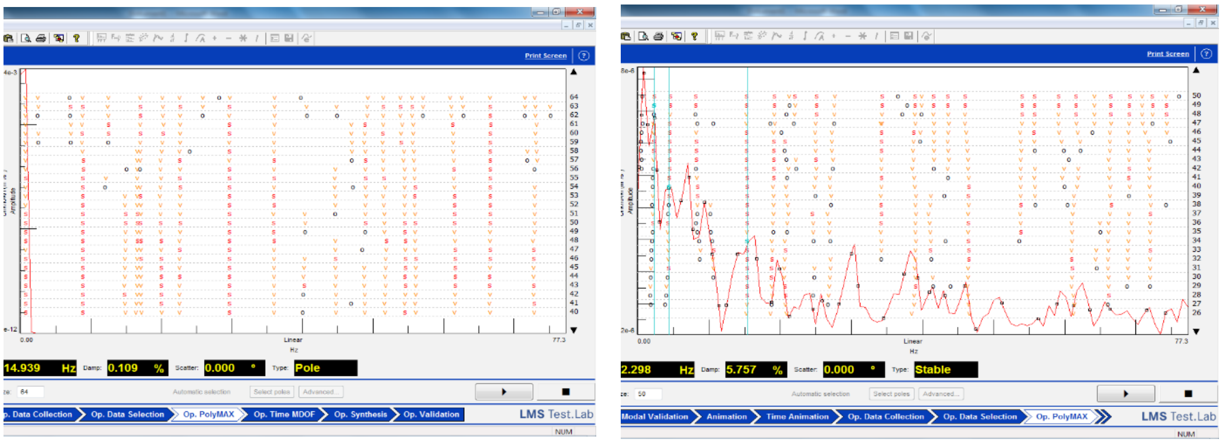

Fig. 22. Stability diagram for the fittest and damaged brickwork (OAM)

Source: own work.

Table 2. Summary of the test frequency of oscillations of a brick wall

Extortion	Fit element	Defective element
Force EAM	865.612 Hz	1 025.81 Hz 1 060.85 Hz 1 112.47 Hz
No force OAM	0.77 Hz	2.28 Hz 4.44 Hz 15.41 Hz
Force OAM	0.80 HZ	0.77 Hz 14.04 Hz

Source: own work.

When assessing the adequacy of the modal analysis method for diagnosing the degradation of masonry structures, it can be considered appropriate for these purposes, even without analysing the results obtained.

Cause-and-effect modelling

Many measures of state acquired in experiments requires the reduction of over measurement, which is possible with the use of the OPTIMUM procedure (statistical evaluation of separate measures):

$$y = -2.68w1 - 0.54\,row1 - 0.49x1 + 2.02w2 + \\ + 0.35row2 + 2.26x2 - 0.07H(f) + 0.06H(f)L + \\ + 0.16g2xy - 92.39ARMS(t) + 12.99bkurt + \\ + 239.69Cs - 200.58I - 44.37$$

An optimised set of symptoms is the basis of constructing cause-and-effect, most often regressive, multidimensional models (Fig. 23). The wellness of the model is evaluated with the help of the determination coefficient (R^2), and the number of component symptoms determines its accuracy (Fig. 24).

For the purposes of this study, results were processed in the OPTIMUM method, and we were able to build a destruction regression model. This approach allowed the differentiation of measurement values for various degradations of the tested materials. It confirmed the effectiveness of the adopted method.

Information processing system diagnostic agent

The ability to quickly identify damage in the diagnosis of elements affecting the operation of the technical facilities was the basis for the creation of the program SIBI (identification research information system). This program is an attempt to implement the software for:

- the acquisition process of vibration,
- the processing of vibration processes,
- examining the interaction of vibration processes,
- symptoms susceptibility testing,
- statistical inference,
- visualisation of analysis results.

The menu of these programs is shown in Figure 25. Figure 26 presents the general idea of an agent system for a critical system in diagnostic observation and information flow in a future diagnostic.

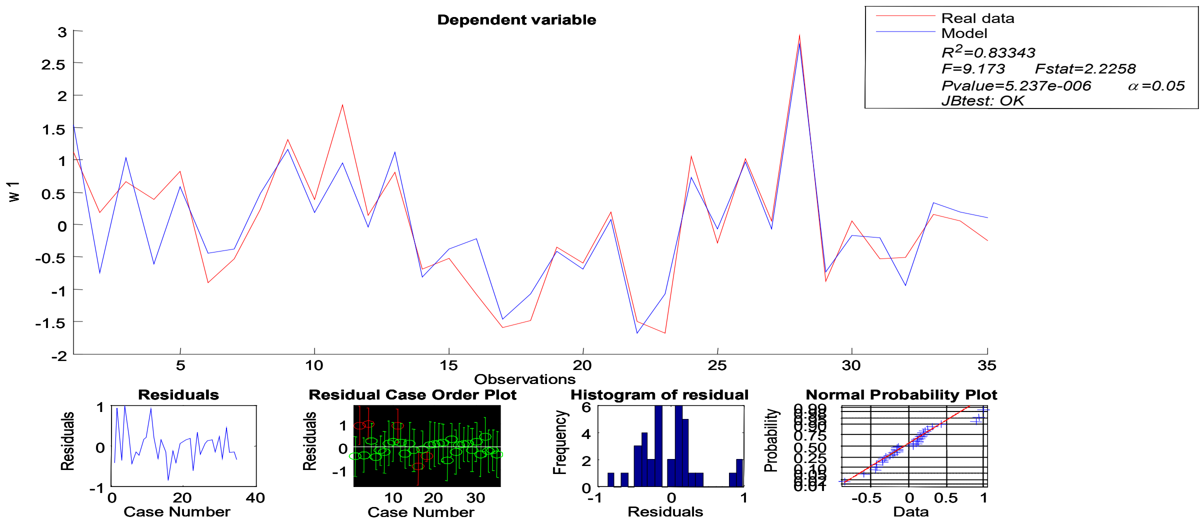

Fig. 23. Regressive determination model

Source: own work.

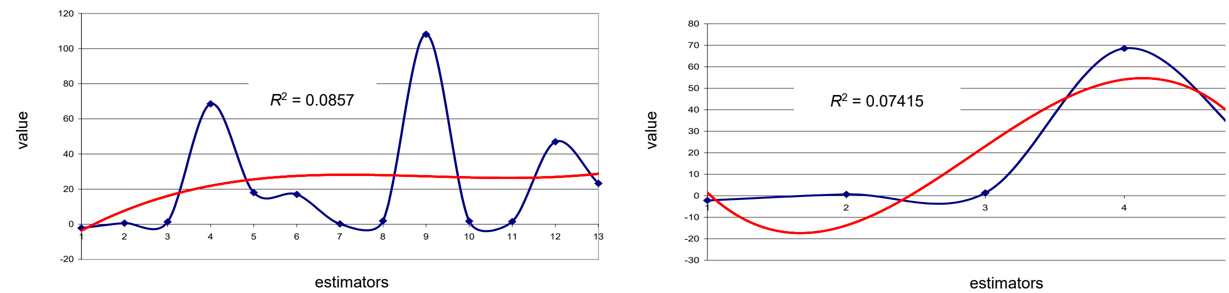

Fig. 24. Number of measures versus accuracy of the model

Source: own work.

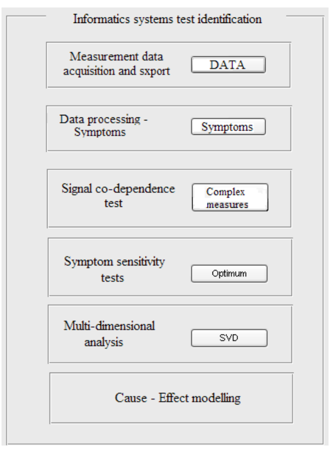

Fig. 25. The main window of the SIBI program

Source: own work.

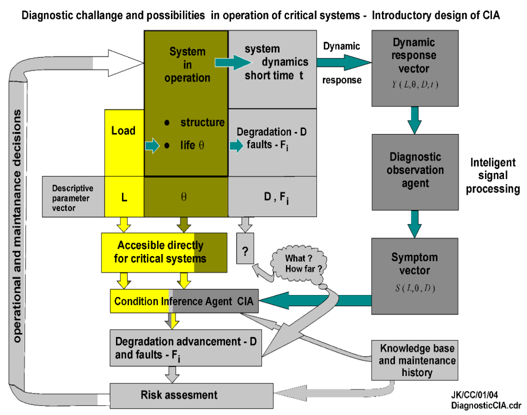

Fig. 26. The information flow and processing in an operating and intelligent monitoring system

Source: own work.

CONCLUSIONS

Methods of identification in the research on building construction (including construction materials) are utility methods to estimate changes in the operating structure. Modal analysis of the varieties for its realisation is increasingly being used by civil engineers, and the modal model accurately reflects the destruction of objects.

Searching for mapping models with models of modal vibration, bench research, and studies on real objects allows for assessing the similarity of the models and the relevance and effectiveness of decision methods. The search for methods of non-destructive testing of materials and structures indicates the possibility of using modal analysis in the assessment of their degradation, as shown in this study.

These studies have been developed or were adapted from MATLAB and practically implemented the following programs: visualisation research results in MS Excel, determination of the vibration process in GENERATE symptoms (correlation and regression testing), and susceptibility testing in OPTIMUM.

The results point to the fact that it is possible to distinguish the status of the degradation properties of brick, which has an impact on the ability to assess the risks and their mechanical properties.

It is, therefore, possible to determine the risks of building structures based on the study of natural frequencies and their characters, using operational modal analysis.

Authors' contributions

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

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

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BADANIA DEGRADACJI KONSTRUKCJI I MATERIAŁÓW BUDOWLANYCH Z WYKORZYSTANIEM PROCESÓW WIBRACYJNYCH

STRESZCZENIE

Istniejące konstrukcje inżynierskie, a zwłaszcza konstrukcje murowe, poddawane są dużym obciążeniom dynamicznym, dobrze odbijanym drganiom w tworzących się procesach. Drgania te mają wpływ na stan robót na placu budowy, gdyż mogą osiągnąć poziom zagrażający stabilności konstrukcji, co zmniejsza bezpieczeństwo osób tam pracujących. Wpływ drgań na konstrukcję objawia się głównie dodatkowymi naprężeniami w przekroju, które zwiększają naprężenia obciążeń statycznych. Ponadto często dochodzi do zmęczenia materiału (skutek oddziaływania klimatu związanego z otoczeniem), co dynamizuje destrukcję obiektu. Obciążenia dynamiczne mogą prowadzić do destrukcji i powodować niszczycielskie skutki w budynkach o różnej konstrukcji lub prowadzić do katastrofalnych zniszczeń. W artykule przedstawiono nowoczesną metodykę nieinwazyjnego badania konstrukcji murowych z wykorzystaniem procesów wibracyjnych. Pokazano również możliwości wykorzystania metod analizy modalnej do oceny stanu zniszczenia elementów i murów z wykorzystaniem procesu drgań i pomiaru drgań. Jest to diagnostyczne podejście wykorzystujące innowacyjne metody badawcze, wsparte technologiami informatycznymi, do badania przydatności materiałów budowlanych i warunków budowy.

Słowa kluczowe: modelowanie, masa, sztywność, tłumienie, sygnał drganiowy, analiza modalna, wykres stateczności, dedykowany system diagnostyczny

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ORIGINAL PAPER

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VEGETATION INVENTORY BEFORE THE RECONSTRUCTION OF ROSNIČKA OUTDOOR SPORTS FIELDS (CITY BRNO, THE CZECH REPUBLIC)

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ABSTRACT

Outdoor sports fields are places for sports activities, but simultaneously, they also serve as living spaces for vegetation. Sports fields are primarily intended for human activities, yet they also serve as habitats for plants. The interaction between sports activities and vegetation is an understudied area, which is the focus of this paper. The aim of the study is to evaluate the biodiversity and ecosystem functions of the vegetation. The selected Rosnička sports field is used by the Sokol Physical Education Unit and is located in the cadastral territory of Brno-Žabovřesky, Czech Republic. A total of 99 plant taxa were found within the locality. As revealed by the canonical correspondence analysis (CCA), diverse parts of the sports field significantly differ in species composition from each other. The vegetation present in the outdoor sports field fulfils several ecosystem functions, such as creating a favourable microclimate, supporting biodiversity, serving an aesthetic function and providing a source of fruit. The quality of the sports turf is essential as it must withstand and facilitate sports activities. Sports facilities not only support the physical and mental health of residents, but also have the potential to synergistically support the biodiversity of urban ecosystems.

Keywords: synanthropic vegetation, urban ecosystem, human civilisation, anthropocene

INTRODUCTION

Parks, outdoor sports facilities and community sports fields are the predominant choices for various sports activities (Booth et al., 2000). Open outdoor spaces are preferred for sports and other physical activities (Brownson et al., 2000; Gilles-Corti & Donovan, 2002; Michael et al., 2010; Bauman et al., 2012; Kerr, Rosenberg & Frank, 2012). Sport affects residents' physical and psychological health and promotes social interactions in communities (Freeman, 2001; Cohen, Inagami & Finch, 2008; Thompson & Kent, 2014). Sport is a structural activity of today's society and plays an important role in a more sustainable future for human civilisation (United Nations [UN], 2015). The world's highest sports organisations (e.g. The International Olympic Committee – IOC) primarily recognise the educational function of sport, but also acknowledge its transformative capacity for its surroundings (International Olympic Committee [IOC], 2019; United Nations Framework Convention on Climate Change [UNFCCC], 2019). Currently, there is limited information on the relationship between sport and the environment (Mallen, Stevens & Adams, 2011; Mal-

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len, 2018; Trendafilova & McCullough, 2018). Nevertheless, a positive association between environmental attitudes and values of the sporting population has been demonstrated (Langenbach, Berger, Baumgartner & Knoch, 2020).

The representation of green infrastructure is a crucial component of outdoor sports complexes (Lachowycz, 2013). The basic function of green infrastructure in outdoor sports facilities is to improve residents' living environment and enhance the environment's aesthetics (Zhou et al., 2022). Green infrastructure is part of the urban ecosystem, which should be in ecological balance and provide several other functions (water protection, microclimate regulation, noise reduction, air filtration and biodiversity protection). By understanding the importance of ecosystem functions, green infrastructure will increase resilience to environmental risks and can contribute to effective solutions in eliminating climate change impacts (Bolund & Hunhamma, 1999; Middle et al., 2014; Knot et al., 2017; Qin, 2020; Francoeur, Dagenais, Paquette, Dupras & Messier, 2021). The biodiversity of green infrastructure in cities is a source of many ecosystem services. As part of urbanisation, many challenges arise in how to use these services. Preserving or revitalising biodiversity is key to achieving sustainability. Green infrastructure in cities plays a fundamental role in maximising positive and eliminating negative impacts on the city (Gómez-Baggethun & Barton, 2013; Sirakaya, Cliquet & Harris, 2018).

The availability of community-built environments such as parks and sports facilities positively affects residents' health (Takagi et al., 2022). In natural environments, the recreational pressure caused by sports activities and the organisation of various sports events is increasing. Currently, there is little information available on studies focused on environmental sustainability and the demand for sports. The behaviour of athletes, sports spectators and local residents is also important from the perspective of environmental impacts (Martins, Pereira, Rosado & Mascarenhas, 2021). Neighbourhood destinations, such as parks and green spaces, hiking trails and attractive scenery, are positively associated with physical activity, especially if they are located close to the residences of their visitors. Destinations further away from home are no longer used as much. Places with high biodiversity near cities are very attractive for sports activities (Keskinen, Rantakokko, Suomi, Rantanen & Portegijs, 2018; Takagi, Kondo, Tsuji & Kondo, 2022). Urban design guidelines, agents and policies supporting people's physical activities in an attractive environment and giving opportunities for inclusive and seasonal use of urban areas lead to multifunctional health of the city, streets and inhabitants (Hidalgo, 2021). The New Urban Agenda was adopted at the Third United Nations Conference on Housing and Sustainable Urban Development held in Quito, Ecuador in 2016. This policy document proposes a concrete action program for transforming and developing human settlements (UN, 2016).

The studied area has been used for sports for a long time. Only minimal care has been given to the green infrastructure. The aim of this study is: (i) to evaluate the biodiversity of vegetation in the conditions of the outdoor sports field; (ii) to evaluate the existing vegetation from the point of view of athletes and participants in sports events; (iii) to assess the ecosystem functions provided by the vegetation of the outdoor sports field that can directly affect athletes and can also contribute to ecological stability.

MATERIAL AND METHODS

Characteristics of the locality

The selected Rosnička outdoor sports fields are used by the Sokol Physical Education Unit. They are located in the cadastral territory of Brno-Žabovřesky (49.205262N; 16.573262E). The area is part of the forest park Wilson Forest (*Wilsonův les*), which was founded in 1882 and has a total area is 8,035 m^2. The altitude is 236 m above sea level. The average annual temperature in the area is 10.2°C and the average annual precipitation is 43.41 mm.

Work on the construction of the outdoor sports field in the forest park began in 1928. The completion of the work and the start of use of the sports arena took place in 1932. Although the sports field is situated at the foot of the northern side of the hill, its location is sufficiently accessible to sunlight both in winter and in summer. The sports complex has a grassy used for sports activities like hammer throw, javelin throw, high jump and ball games. There is a running track around this oval grassy field and a long jump track and landing pad at the verge of the grassy area. There used to be tribunes for spectators; however, they are not used anymore, and spontaneous vegetation grows over them. There are also remains of an orchard planting in the sports field.

Characteristics of stands in the sports fields

The sports field was divided into 5 areas, each with a different character of use. Their spatial arrangement is demonstrated in Figure 1.

Area A: It is the central location of the entire sports complex. There is a running truck with a long and high jump area, a javelin, hammer, cricket ball and discus throwing area. It is a flat area with an extensively managed sports pitch (grass) that is maintained by mowing to a height of 20–30 mm.

Area B: There is the former stand for the spectators of the athletic events. At the moment, the tribune is not in use. Benches and metal structures were removed. The sloping terrain remained modified in the form of terraces, reinforced with concrete lintels, and with stairs in the right, middle and left parts. Spontaneous vegetation, which is mowed twice a year, grows there.

Area C: Unused area left to be overgrown by spontaneous vegetation. In 2019, this area was cleared and fully grown trees and bushes were removed. The biomass of woody plants was taken away from the sports field. Since then, this part has not been maintained.

Area D: There are remains of an orchard planting and a reinforced footpath used for running. The terrain there is sloping and, on the northern and eastern sides, it is fortified with a stone wall to prevent landslides from the surrounding slopes. The vegetation is not maintained there.

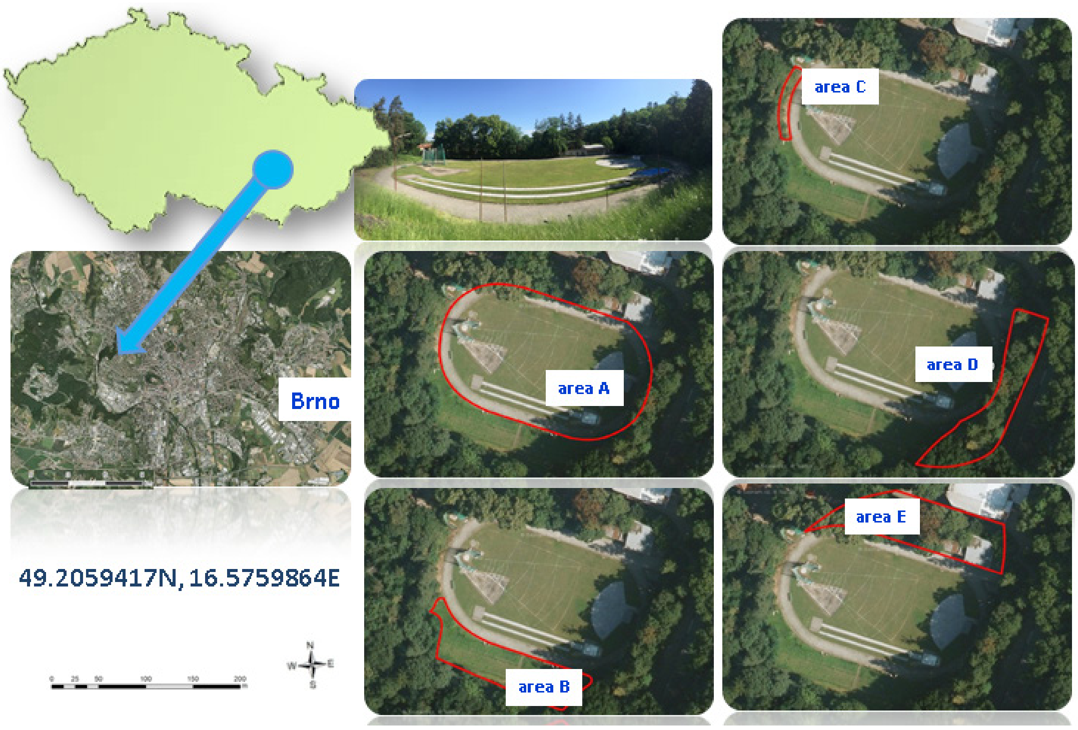

Fig. 1. Location of the Rosnička sports fields and the delimitation of its 5 areas

Source: own work.

Area E: It is the area around the administrative building. There are mainly fully grown trees, which often disrupt the foundations of the building and walkways with their roots. It is a flat terrain. The vegetation is not maintained there.

Assessment of vegetation in the sports area

The determination of the biodiversity of the vegetation was carried out using a botanical inventory, and the intensity of occurrence of the identified plant taxa was also evaluated. At each site, the species that were found were recorded. Data collection was carried out on 30/05/2022, 12/06/2022 and 25/08/2022. Scientific names were used consistent with Kaplan et al. (2019).

The occurrence of individual plant species at the monitored locations was processed by multivariate analysis of ecological data. The choice of the best analysis was guided by the length of the gradient determined by the correspondence analysis (DCA) segment. Furthermore, canonical correspondence analysis (CCA) was used. Statistical significance was determined using a Monte Carlo test with 999 calculated permutations. The data was processed using the computer program Canoco 5 (Ter Braak & Šmilauer, 2012).

RESULTS AND DISCUSSION

A total of 99 plant taxa were found within the entire sports field. A breakdown of the number of taxa divided into biological groups in the monitored areas is shown in Figure 2. In Area B, 47 plant taxa were found, and in Area C, 46 plant taxa. A total of 25 plant taxa were found in Area D, 19 plant taxa in Area E and at least 16 plant taxa in Area A.

The CCA analysis defines the spatial arrangement of individual plant taxa and delimited areas. The results of the CCA analysis are significant at the significance level $\alpha = 0.01$. The results are, therefore, statistically highly significant. According to the ordination diagram (Fig. 3), the plant taxa can be divided into 4 groups.

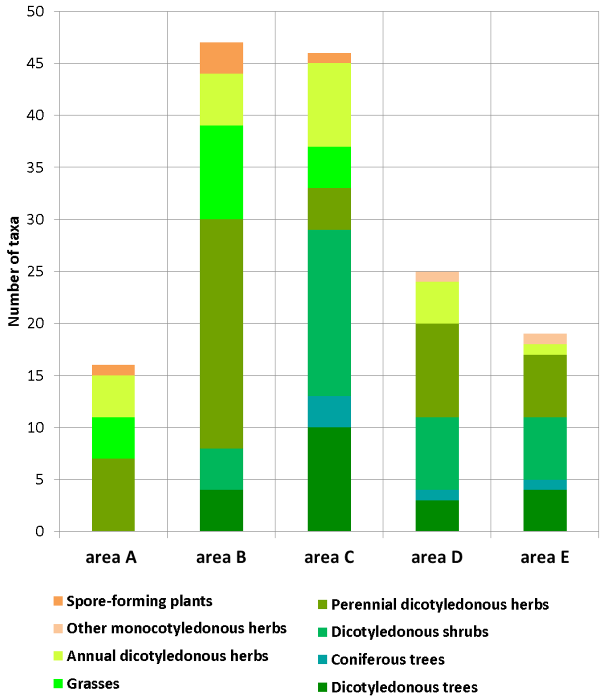

Fig. 2. Plant taxa and their groups found in the studied areas of the sports complex

Source: own work.

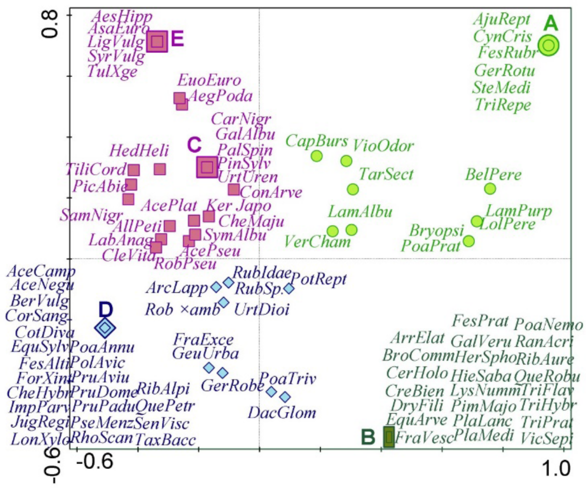

Fig. 3. Ordination diagram expressing the relationship of found plant taxa and monitored areas of the sports field (CCA analysis results; pseudo $F = 1.1$; $p = 0.01$)

Source: own work.

The first group of taxa was mainly found in Area A: *AjuRept – Ajuga reptans*, *BelPere – Bellis perennis*, *Bryopsis*, *CapBurs – Capsella bursa-pastoris*, *CynCris – Cynosurus cristatus*, *FestRubr – Festuca rubra*, *GerRotu – Geranium rotundifolium*, *LamAlbu – Lamium album*, *LamPur – Lamium purpureum*, *LolPere – Lolium perenne*, *PoaPrat – Poa pratensis*, *SteMedi – Stellaria media*, *TarSec – Taraxacum* sect. *Taraxacum*, *TriRepe – Trifolium repens*, *VerCham – Veronica chamaedrys*, *VioOdor – Viola odorata.*

The second group of taxa occurred mainly in Area B: *ArrElat – Arrhenatherum elatius*, *BroComm – Bromus commutatus*, *CerHolo – Cerastium holosteoides*, *CreBin – Crepis biennis*, *DryFili – Dryopteris filix-mas*, *EquAre – Equisetum arvense*, *FestPrat – Festuca pratensis*, *FraVesc – Fragaria vesca*, *GalVeru – Galium verum*, *HerSpho – Heracleum sphondylium*, *HieSaba – Hieracium sabaudum*, *LysNumm – Lysimachia nummularia*, *PimMajo – Pimpinella major*, *PlaLanc – Plantago lanceolata*, *PlaMedi – Plantago media*, *PoaNemo – Poa nemoralis*, *QeuRobu – Quercus robur*, *RanAcri – Ranunculus acris*, *RibAure – Ribes aureum*, *Triflav – Trisetum flavescens*, *Trihybr – Trifolium hybridum*, *Triprat – Trifolium pratense*, *VicSepi – Vicia sepium*.

The third group in Area C and Area E: *AcePlat – Acer platanoides*, *AcePse – Acer pseudoplatanus*, *AegPoda – Aegopodium podagraria*, *AesHipp – Aesculus hippocastanum*, *AllPeti – Alliaria petiolata*, *AsaEuro – Asarum europaeum*, *CarNigr – Carex nigra*, *CheMaju – Chelidonium majus*, *CleVita – Clematis vitalba*, *ConArve – Convolvulus arvensis*, *EuoEuro – Euonymus europaeus*, *GalAlbu – Galium album*, *HedHeli – Hedera helix*, *KerJapo – Kerria japonica*, *LabAnag – Laburnum anagyroides*, *LigVulg – Ligustrum vulgare*, *PalSpin – Paliurus spina-christi*, *PicAbie – Picea abies*, *PinSylv – Pinus sylvestris*, *RobPseu – Robinia pseudoacacia*, *SamNigr – Sambucus niger*, *SymAlbu – Symphoricarpos albus*, *SyrVulg – Syringa vulgaris*, *TiliCord – Tilia cordata*, *TulXge – Tulipa ×gesneriana*, *Urt Uren – Urtica urens*.

The fourth group occurred in Area D: *AceCamp – Acer campestre, AceNegu – Acer negundo*, *ArcLapp – Arctium lappa*, *BerVulg – Berberis vulgaris*, *CheHybr – Chenopodium hybridum*, *CorSang – Cornus sanguinea*, *CotDiva – Cotoneaster divaricatus*, *DacGlom – Dactilis glomerata*, *EquSylv – Equisetum sylvaticum*, *FesAlti – Festuca altissima*, *ForXint – Forsythia ×intermedia*, *FraExce – Fraxinus excelsior*, *GerRobe – Geranium robertianum*, *GeuUrba – Geum urbanum*, *ImpParv – Impatiens parviflora*, *JugRegi – Juglans regia*, *LonXylo – Lonicera xylosteum*, *PoaAnn – Poa annua*, *PoaTriv – Poa trivialis*, *PolAvic – Polygonum aviculare*, *PotRept – Potentilla reptans*, *PruAviu – Prunus avium*, *PruDome – Prunus domestica*, *PruPadu – Prunus padus*, *PseMenz – Pseudotsuga menziesii*, *QuePetr – Quercus petraea*, *RhoScan – Rhodotypos scandens*, *RibAlpi – Ribes alpinum*, *Rob×amb – Robinia ×ambigua*, *RubIdae – Rubus idaeus*, *Rubsp. – Rubus sp.*, *SenVisc – Senecio viscosus*, *TaxBacc – Taxus baccata*, *UrtDioi – Urtica dioica.*

The monitored areas of the sports field provide a living space for various life forms of plants – ranging from annual and perennial herbs, to shrubs and trees. It follows from the CCA analysis that differently used parts of the sports field differ significantly from each other in the species composition of the vegetation. Plant taxa are critical for biological relevance, defined as the number of other organisms dependent on a given plant taxon. Organisms use plants as a food source, a substrate, a shelter or a place for reproduction. Some plant taxa, particularly high-biomass and long-life trees, may be crucial to the survival of hundreds or thousands of other organisms, while some low-frequency, low-biomass species may be almost irrelevant (Tyler, Herbertsson, Olofsson & Olsson, 2021). The following woody plants: *Quercus petraea*, *Q. robur*, *Acer campestre*, *A. pseudoplatanus*, *Picea abies*, *Pinus sylvestris*, *Prunus avium*, *P. domestica*, *P. padus*, *Rubus idaeus*, *Tilia cordata*; and herbs: *Dactylis glomerata*, *Plantago lanceolata* and *Trifolium pratense* have high biological relevance from the taxa identified in the studied sports field.

Urbanisation leads to the fragmentation of natural habitats and strongly affects communities. The richness of plant species is taxonomically much higher in the city than out of it due to exotic plants that have been planted in places accidentally or intentionally for ornamental purposes. Cities can also be richer in native plant taxa (Bonthoux, Brun, Di Pietro, Greulich

& Bouché-Pillon, 2014). In recent years, attention has been paid to the loss of insect biodiversity – especially the decline of pollinators (Sorg, Schwan, Stenmans & Müller, 2013). Nectar and pollen production can be considered an indicator of the importance of plant taxa to pollinators. Naturally, plants also provide shelter and are a source of non-floral food for some insect larval stages (Baude et al., 2016). The biodiversity of vegetation is substantially influenced by how it is used and how vegetation is managed. An approach using the principles of urban agriculture can lead to the stabilisation of ecosystems in peri-urban areas (Nowysz, Mazur, Vaverková, Koda & Winkler, 2022). The species richness of the vegetation of the monitored sports field is a prerequisite for the creation of a rich ecosystem. The species composition of vegetation in urbanised areas is in the hands of people who directly decide which species composition of plant taxa will be sown or planted.

The most important location for the sports complex is Area A, which is used as the main place for sports activities. The taxa dominating there are grasses (*Festuca rubra*, *Lolium perenne*, *Poa pratensis*) and perennial dicotyledonous herbs typical of lawns (*Ajuga reptans*, *Bellis perennis*, *Bryopsis*, *Trifolium repens*). Lawns are a prominent element of outdoor sports fields and all public greenery, requiring high maintenance (Hedblom, Lindberg, Vogel, Wissman & Ahrné, 2017; Knot et al., 2017). The way of maintenance changes the ecosystem functions of lawns (Wheeler et al., 2017). Intensive lawns managed with herbicides, fertilisers, watering and frequent mowing have high aesthetic value (Norton et al., 2019; Yang, Ignatieva, Larsson, Zhang & Ni, 2019), but also negative characteristics such as intensive water use, nutrient runoff and low species diversity (Ramer & Nelson, 2020). Extensive grasslands, which are characterised by lower fertiliser use and less frequent mowing (Hugie & Watkins, 2016; Aronson et al., 2017), are often composed of spontaneous plant taxa that can be food sources for pollinators (Lerman & Milam, 2016; Norton et al., 2019).

The presence of extensively managed urban grasslands in urban areas has been constantly increasing due to the lower management costs and their high biodiversity (Watson, Carignan-Guillemette, Turcotte, Maire & Proulx, 2020; Lampinen et al., 2021). The turf at the monitored sports field must withstand sports activities and trampling (frequent stepping). Due to the limited financial resources of the operator, only extensive management is provided to the lawn. This is manifested in a higher representation of spontaneous plant taxa (dicotyledonous taxa). In the case of lawn restoration, the appropriate choice of species composition of lawns will be essential. Ornamental, recreational and sports fields are not considered semi-natural vegetation because they require a high level of human management such as fertilisation, irrigation, mowing, etc. (Ignatieva & Hedblom, 2018). The input level depends on selecting appropriate taxa and grass cultivars (Christians, Patton & Law, 2016). Grasslands requiring only low inputs must be tolerant to abiotic and biotic stresses, have low nutrient and water demands and be competitive to minimise weed occurrence (Hugie, Yue & Watkins, 2012). Dicotyledonous taxa such as *Achillea millefolium*, which tolerate frequent mowing, trampling, drought and extensive management, are also recommended for extensive grasslands (Pornaro, Fidanza & Macolino, 2023).

In the rest of the locations, a high proportion of taxa that can be considered as spontaneous vegetation. The importance of spontaneous vegetation in the green infrastructure of cities is highlighted by Xiao-Peng, Shu-Xin, Kühn, Dong and Pei-Yao (2019), namely the importance of biological diversity and a wide range of sociocultural factors. Incorporating spontaneous vegetation into green-space design-planning can help achieve greater sustainability in cities. The ubiquity of the garden style in green infrastructure is a common trend and leads to the selection of the same ornamental plant taxa, the same forms of planting designs, etc. This leads to the promotion and development of a market for non-native plant taxa that are very similar all over the world, which has caused a loss of ecological functions of landscape and leads to homogenisation (Quigley, 2011).

The green infrastructure of sports venues affects spectators at sporting events (Edwards, Knight, Handler, Abraham & Blowers, 2016; Pereira, Camara, Ribeiro & Filimonau, 2017). Urban vegetation is also very beneficial for the education of the younger generation (Jorgensen & Keenan, 2012). Vegetation provides both ecosystem and cultural functions. Spectators and athletes appreciate above all the aesthetic value of vegetation. From the aesthetic point of view, taxa that form conspicuous flowers are perceived positively, such as *Ajuga reptans*, *Bellis perennis*, *Cotoneaster divaricatus*, *Euonymus europaeus*, *Forsythia ×intermedia*, *Laburnum anagyroides*, *Lamium album*, *Ligustrum vulgare*, *Lonicera xylosteum*, *Lysimachia nummularia*, *Rhodotypos scandens*, *Syringa vulgaris*, *Trifolium hybridum*, *T. pratense*, *T. repens*, *Tulipa ×gesneriana*, *Veronica chamaedrys* and *Viola odorata*.

Urbanisation transforms natural landscapes into engineered structures (buildings, parking lots, streets, squares, etc.), leading to an increase in ambient temperature – commonly known as the urban heat island effect (Li & Wang, 2021). An essential function of vegetation and particularly trees is air cooling, especially in the summer months and the elimination of heat islands in urban areas (Gómez-Baggethun & Barton, 2013; Gillner, Vogt, Tharang, Dettmann & Roloff, 2015). This fact in humans is limited by heat stress and the discomfort associated with it (Paschalis, Chakraborty, Fatichi, Meili & Manoli, 2021). The creation of a favourable microclimate is an overlooked but irreplaceable function of vegetation on outdoor sports grounds. Another interesting group of plants are fruit trees; they produce fruit that can be consumed. On the other hand, their cultivation is associated with a higher demand for their maintenance. In the studied area there are remains of the original planting of fruit trees, such as *Juglans regia*, *Prunus avium*, *P. domestica*, *Ribes aureum*, *Rubus* sp. and *R. idaeus*. In the case of reconstruction of the sports field, there should be a space for planting fewer demanding types of fruit trees.

The management of the vegetation of sports facilities is linked with the production of waste biomass. Management of vegetation biomass and biological waste is not currently being handled within the area. According to Xin et al. (2020) unused plant biomass is processed mainly by landfilling and burning, which is costly and inefficient. A more environmentally friendly method is the processing of biological waste by composting (Wei et al., 2017; Yasmin et al., 2022). In the composting process, microorganisms convert biomass into stable organic fertiliser (Zhang et al., 2020; Rashid & Shahzad, 2021; Thomson, Price, Arnold, Dixon & Graham, 2021; Chorolque et al., 2022; Xu et al., 2022). Compost can be used to improve soil quality (Toledo, Siles, Gutiérrez & Martín, 2018; Longhurst et al., 2019) and it is possible to use it directly in the sports field. This method of handling local biological waste and its subsequent local use fits into the circular bioeconomy strategy (Marcello, Di Gennaro & Ferrini, 2021; Torrijos, Dopico & Soto, 2021; Zhou et al., 2022). Creating a local composting facility would bring several benefits. The amount of waste that must be transported from the sports field would be reduced, and at the same time, fertiliser that might find application in the revitalisation and maintenance of local vegetation would be produced. Unremoved vegetation biomass in combination with dry and warm weather can create a fire risk (Lazarus et al., 2020; Campos & Abrentes, 2021). The species composition of the vegetation and the condition of the vegetation are very important factors for the occurrence of fire (Piwnicki, Szczygieł, Ubysz & Kwiatkowski, 2006; Ubysz & Szczygieł, 2006; Marcisz et al., 2019). The development of monitoring systems using remote sensing, geographic information systems and multispectral imaging can be seen as an evidence of the importance of green infrastructure in cities. Awareness and knowledge about the state of vegetation provides information on the provision of ecosystem functions as well as about the risk of fires (Wang, Rich, Price & Kettle, 2004; Lotfata, 2021; Sikorska, Ciężkowski, Babańczyk, Chormański & Sikorski, 2021).

The design and construction of sports facilities should be focused on the needs of local urban residents and should lead to the improvement of the urban environment (Zhang et al., 2021). Planning and construction must include a green infrastructure rich in native plant taxa species. Globalisation and urbanisation are the main drivers of the homogenisation of urban landscapes around the world; therefore, the flora and fauna of cities is remarkably similar in different parts of the world despite geographical and climatic differences (McKinney, 2006). Sports facilities support the physical and mental health of residents, but on the other hand, they also have the potential to synergistically support the biodiversity of urban ecosystems.

CONCLUSIONS

The monitored areas of the sports field provide a living space for various life forms of plants – ranging from annual and perennial herbs, to shrubs and trees. A total of 99 plant taxa were found. The CCA analysis proved that differently used locations differ significantly from each other in species composition. The vegetation of the outdoor sports field fulfils several ecosystem functions, such as the creation of a favourable microclimate, the support of biodiversity, aesthetic functions and serves as a source of fruit. The quality of the sports fields is essential as it must endure and enable sports activities.

The ecosystem functions provided by plant taxa may differ in nature. The most important factor was the increase in the vegetation diversity. By selecting appropriate native species, urban planners can ensure the species stability of the vegetation or even increase its species diversity. Interestingly, the discovery of the taxon Rhodotypos scandens – a soil-cultivated ornamental plant, has already successfully penetrated urban ecosystems.

Less favourable ecosystem functions include the production of allergenic pollen by some taxa, which can affect the health and fitness of athletes. Of the plant taxa found, pollen is highly allergenic – *Arrhenatherum elatius*, *Dactylis glomerata*, *Festuca pratensis*, *F. rubra*, *Chenopodium hybridum*, *Juglans regia*, *Lolium perenne*, *Picea abies*, *Pinus sylvestris*, *Plantago lanceolata*, *P. media*, *Poa annua*, *Robinia pseudoacacia*, *Sambucus nigra*, *Taraxacum* sect. *Taraxacum*, *Tilia cordata* and *Urtica dioica*. Trees only produce pollen over a relatively short period, and it is impossible to regulate the production of allergenic pollen. Herbs, including grasses, usually flower repeatedly; however, pollen production can be regulated by mowing.

Vegetation maintenance is linked with the production of waste biomass. In the area, the produced waste is treated as ordinary municipal waste. It would be appropriate to use the biological waste generated during the maintenance of the vegetation for composting and to use the final compost as fertiliser for the existing vegetation of the sports field.

According to the results, the representation of non-native taxa is not dominant, and there is a risk that their proportion will increase. This increase may be due to climate change, causing a decline in native taxa and the deliberate seeding of non-native taxa. Urban planners and architects should be aware of the suitability and unsuitability of the plant taxa that they plan to incorporate into their designs.

Outdoor sports fields have the potential to support the physical and mental health of residents. The area of the outdoor sports field opens up new possibilities for vegetation due to its different uses. The combination of an outdoor sports field with the urban vegetation will have a synergistic potential that will support the residents' quality of life and can simultaneously increase the biodiversity of urban ecosystems.

Authors' contributions

Conceptualisation: J.W. and L.H.; methodology: J.W. and J.B.; validation: J.W. and P.M.B.; formal analysis: J.M. and Y.R.L.; investigation: P.M.B.; resources: J.W.; data curation: J.W.; writing – original draft preparation: J.B.; writing – review and editing: P.M.B. and Y.R.L.; visualisation: J.W.; supervision: J.W. and L.H.; project administration: J.W.; funding acquisition: J.W.

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

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INWENTARYZACJA ROŚLINNOŚCI PRZED REKONSTRUKCJĄ TERENU SPORTOWEGO ROSNIČKA (MIASTO BRNO, REPUBLIKA CZESKA)

STRESZCZENIE

Obiekty sportowe są miejscami aktywności, ale również środowiskiem życia dla roślinności. Celem pracy jest ocena bioróżnorodności i funkcji ekosystemowych roślinności na tego typu obiektach. Wybrany teren sportowy Rosnička jest użytkowany przez Towarzystwo Gimnastyczne Sokół. Znajduje się w obrębie katastralnym Brno-Žabovřesky (Republika Czeska). Łącznie zidentyfikowano tam 99 taksonów roślin na całym obszarze. Kanoniczna analiza korespondencji (CCA) wskazuje, że różnie wykorzystywane siedliska znacząco różnią się pod względem składu gatunkowego występującej tam roślinności. Na terenie obiektu sportowego roślinność pełni wiele funkcji ekosystemowych (m.in. tworzenie korzystnego mikroklimatu, wspieranie bioróżnorodności) i funkcje estetyczne oraz stanowi źródło owoców. Kluczowym elementem są trawniki sportowe, które muszą umożliwić uprawianie sportu. Tereny sportowe przyczyniają się do wspierania zdrowia fizycznego i psychicznego mieszkańców, ale mają także potencjał do synergicznego kształtowania bioróżnorodności ekosystemów miejskich.

Słowa kluczowe: roślinność synantropijna, ekosystem miejski, cywilizacja ludzka, antropocen

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GENERATIVE SHAPING IN SEARCH OF MATERIAL AND STRUCTURAL OPTIMISATION OF SMALL STRUCTURAL FORMS

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ABSTRACT

In the 21st century, the most advanced digital methods have allowed structure design, analysis and multi-directional optimisation based on multiple parameters. Mathematical algorithms based on proportionality requirements enable the software to create an individual solution for the specified boundary conditions. This is particularly interesting from the point of view of prefabrication and material engineering, which is now more often characterised by the idea of post-Fordism, where the desire for unification does not exclude the creative search for individual solutions. The research presented in this paper attempts to answer how parametric designing conducted on bar trusses can be implemented into the optimisation of structural elements. The methodology employed in the study involved using of parametric design tools to create a symmetrical truss model, assess its advantages and challenges, and consider load cases. The information provided in the conclusion highlights the evolution of parametric design – which has not only revolutionised architecture and construction by inspiring unconventional forms, but has also facilitated the optimisation of design processes, offered new design possibilities and enabled effective control over various modelling aspects, confirming its invaluable role in both architecture and construction.

Keywords: algorithmic design, digital fabrication, generative design, ICT productivity, interdisciplinary design, parametric design, structural optimisation

INTRODUCTION

Parametric modelling, parametric design and parametric architecture are increasingly used to refer to building design where digital tools have been used in the execution. This proceeding particularly applies to curvilinear, non-orthogonal forms and any structural elements. Parametric design links the operation of the model to the adoption of 'parameters'. In computer design, the term was applied in the 1970s by Steve Coons, who proposed a description of curves using parametric equations. The next step was the possibility of using parametric features in digital design, first introduced by Mark Gross in his doctoral thesis in which he found that these features were helpful in typical variable forms. Josef Serrano Gómez applied a clear recognition of the parametric technique in architectural solid modelling in 1993 (Alvarado, Lyon & Cendoya, 2015).

This study analyses tools supporting the parametric design of structural elements and parametric architectural design. The literature review helps identify the direction of development of digital design tools and to determine to what extent parametric modelling improves the design process. Based on the literature review and the examples presented, the

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question arises whether parametrisation and the use of digital design tools facilitate the design of structures. In the paper, a model of the truss structure was presented, created using the visual programming software – Dynamo. The calculations for part of the structure were made in Robot Structural Analysis Professional. The research hypothesis of the study is parametric modelling as a tool to support design.

LITERATURE REVIEW

An early example of parametric design is the model of the temple in the Colonia Güell created by Antonio Gaudi. The Catalan architect began work on the project as early as 1890. Despite not having access to digital design tools, Gaudi demonstrated a high skill level in composing shapes (Markert & Alves, 2016). The architect worked on the design of the column for two years (Fig. 1). Through manipulating simple geometries, he achieved an original form like the organic shape of plants (Dixit, Stefańska & Musiuk, 2021). The sketches, models and drawings left by Gaudi provided sufficient data for subsequent successors wishing to complete the work of the deceased.

Fig. 1. Gaudi's model of the Sagrada Familia temple

Source: own work.

Serrano presented work supplementing Gaudi's design of the Sagrada Familia temple with computer models. These models were based on adjustable intersection surfaces. The surfaces were subdivided into helicoids, hyperbolic paraboloids and hyperboloids. The subdivision procedure enabled accuracy, allowing remote fabrication of stone elements without needing to be sent back to the construction site to match the adjacent details (Serrano, Coll, Melero & Burry, 2022).

Algorithmic thinking

Algorithmic design (AD) is a subset of generative design (GD) that specifically employs algorithms to create of design models. In the case of AD, a distinct connection exists between the algorithm and the resulting design, exists between the algorithm and the resulting design. AD offers a higher level of precision and control compared to GD and frequently leads to designs that are predictable and can be replicated (Caetano, Santos & Leitão, 2020).

The parameterisation of the model is applicable when a change in a parameter (i.e. information) affects the geometry of the form and its structure. Parametric design is not based on an intuitive search for a solution but on a step-by-step technique of introducing variables according to specific rules that produce an initial result. Thinking about the process in this way refers to algorithmic thinking. Architects or designers wishing to assist with a parametric model face the challenge of mastering algorithms based on mathematics (Kurcjusz, Stefańska, Dixit & Starzyk, 2022). The essence of design is to understand the process, but practice in using the software is also essential. Algorithmic thinking allows manoeuvring results, controlling, analysing and optimising the design of the solution space (Lehmann, 2023). The assumptions of a design concept created in the imagination can only be verified and optimised once a parametric model has been created. Since 1990, parametric design has influenced the development of digital architectural design, which can be divided into two parts: conceptual parametric architectural design and structural parametric design.

Conceptual parametric architectural design

Conceptual parametric architectural design focuses on the parameterisation of a design model. In this approach, changes in parameters – which represent critical pieces of information – directly influence both the geometry and the form's overall structure. Unlike intuitive searches for solutions, parametric design relies on a systematic technique of introducing variables according to specific rules. This method yields an initial result, making it an excellent example of algorithmic thinking. In conceptual architectural design, the parameters introduced are the most important – not the shape. Thanks to their variability, the form of the building can be easily configured.

Structural parametric design

In structural parametric design, the data refers to the 3D embedded object (Aranburu, Camba, Justel & Contero, 2023). Parametricity in structural design is used most effectively when designing large structures, airports, halls and tall buildings. This is due to the complexity of the structure, as well as the number of elements required. A small change in the geometry of the form makes it necessary to generate a new analytical model. The frequency of changes and the duration of the design process using traditional methods have sparked the desire to integrate digital architectural and structural models (Bialozor & Olszowski, 2017).

An interesting issue is the parametricity of tall buildings, where the design is created with defined rules in its early stages. Therefore, it is difficult to incorporate changes resulting from analyses or client requests. Unfortunately, using AutoCAD software does not make it easy to modify a whole project consisting of many elements (Khoshamadi et al., 2023). Parametricity in a structural model is a complex process. However, according to Suyoto, Indraprastha and Purbo (2015), it senses the architect's mind in structural design and connects the constructors' design with its form's creators. The structural part of a building is developed after the architectural structure is determined. This approach limits the role of the constructor in solving the problems present in the project. It does not lead to a link between the architect's concept and the structural solution. Emerging tools to overcome the previously mentioned limitations provide a cost-effective solution to explore optional design solutions (Khoshamadi et al., 2023).

Structural optimisation

Optimisation algorithms, considering the structure of the building, have found application – especially in structural optimisation. The traditional structural design uses design variables for which arbitrary initial values are given. Structural analysis is carried out to obtain an answer, and the design variables are modified intuitively. In the final stage, the design process ends when good values of the imposed requirements are obtained, often without considering alternatives or not enough of them. Structural optimisation in structural design offers some advantages, including the automatic finding of design solutions that consider the imposed conditions. In addition, optimisation tools can support a designer's decision-making. If the design solution is unsatisfactory, the designer can change the design parameters, material properties or component geometry. It is also possible to impose additional constraints on the optimisation assignment. When considering complex structures, structural optimisation helps to find a feasible solution and, in situations where the designer does not use the key, provides better insight into the behaviour of the structure. A final aspect that is a definite advantage of optimisation is the trade-off between the structural layout and the associated costs (Hu, Song, Song & Li, 2023).

Defined and quantifiable financial benefits are advantageous when convincing an investor to invest. An example is steel weight reduction, a necessary element during building construction. The algorithm makes it possible to optimise material distribution by adjusting the span of the structural beams more favourably due to choosing a lower story height or changing the steel grade and cross-section of the elements. The optimisation algorithm can also be used to carry out static calculations. The advantage is the non-stereotypical thinking of the program and the ability to carry out hundreds of calculation variants in a short time (Stefańska & Rokicki, 2022).

Topological optimisation

Topological optimisation is a rationalisation method that uses computational schemes to achieve optimised material distribution. However, the user must define a set of loads and constraints in the solution space. Optimisation increases productivity and design efficiency in areas that do not contribute significantly. On the other hand, unnecessary material is removed, reducing the structure's weight and lowering the vibration analysis results (Yildirim, 2022).

Topological optimisation enables the creation of forms using several computational methods. The basis of all techniques is the finite element method (FEM). The use of the method allows for the greatest stiffness of the structural system to be achieved. Evolutionary methods for creating structural forms play a significant role in topological optimisation. In the early 1990s, the evolutionary structural optimisation (ESO) method was developed, which consists of dividing a given volume into sections, enabling a subsequent analysis of the forces acting on the section. The support and attachment points are determined with the forces applied in the next step. Once the analysis has been carried out, the excessive material is removed, leaving only the part necessary to transmit the specified forces. Analysis and removal are repeated until the optimum is reached. This procedure is reminiscent of the adaptation of organisms to live in nature – hence the name 'evolutionary algorithms' (Zwierzycki, 2013). The idea is, therefore, based on evolving the structure toward the optimum by removing the elements with the lowest stresses. Another optimisation method derived from the ESO method is the additive evolutionary structural optimisation (AESO) method. An inverted process logic characterises the AESO method.

The use of the method starts at selected points by adding the necessary material in the places most needed (according to the optimisation criteria). The method has not proved successful in all cases (the solutions are correct, but the material used is too high). These findings resulted in the development of an enhanced bidirectional evolutionary structural optimisation (BESO) procedure. Initially published in 2006 by a team led by Mike Xie, one of the creators of ESO, the BESO method combines the principles of ESO and AESO. It effectively eliminates redundant material while incorporating necessary components in specific areas (Januszkiewicz & Banachowicz, 2017). When comparing the BESO method with ESO, it is evident that the former is considerably more efficient, as it is not limited to the removal of redundant material alone.

MATERIAL AND METHODS

In this paper, a parametric truss model was designed using Autodesk Revit 2023, Autodesk Robot Structural Analysis Professional 2023 and the Dynamo add-on. The script creating the geometric model of the truss was made using in the Dynamo add-in. In contrast, the geometric representation was controlled in the Dynamo view window and Robot Structural Analysis software.

The executed script allows the creation of a symmetrical truss in which it is possible to change the distance between the truss bars, the height of the truss and the number of truss fields. However, it should be noted that the executed script generates correct results when the result $n/2$ is an odd number, where n is the number of truss fields. The model uses three cross sections – TREC 80×80×8, HEB 220, HD 360×196 – and defines support conditions.

Combining the Dynamo add-on with the Robot program generated the quantities necessary for further calculations. To perform the model integrated with the Robot program, the following load cases were assumed (calculations of the values of the forces entered the program through the Dynamo add-on are summarised later in this paper):

- permanent loads,
- uniformly and unevenly distributed snow loads,
- wind loads, four cases,
- service loads.

The tools used to design the model made it possible to determine the benefits parametric design brings and the difficulties encountered.

Design tool

The script creating the truss geometry was created in the Dynamo add-on. To execute the algorithm, selecting the necessary design assumptions was performed. An essential element is the selection of the truss type. It should be noted that the script generates a symmetrical truss model, so it is necessary to specify the

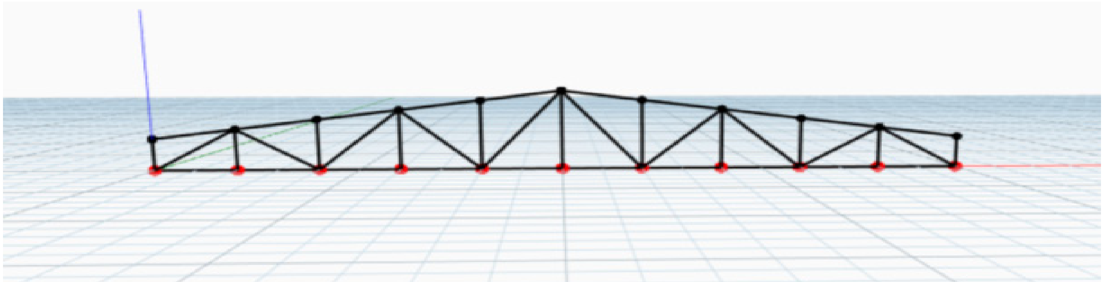

Fig. 2. Truss model made with a script in Dynamo

Source: own work.

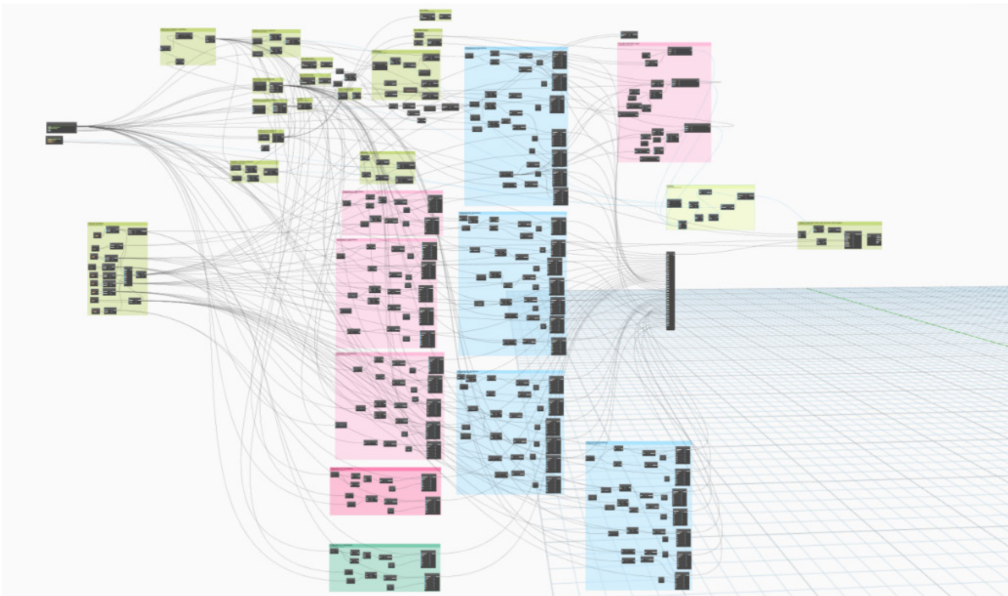

Fig. 3. The overall look of the script in the Dynamo add-on

Source: own work.

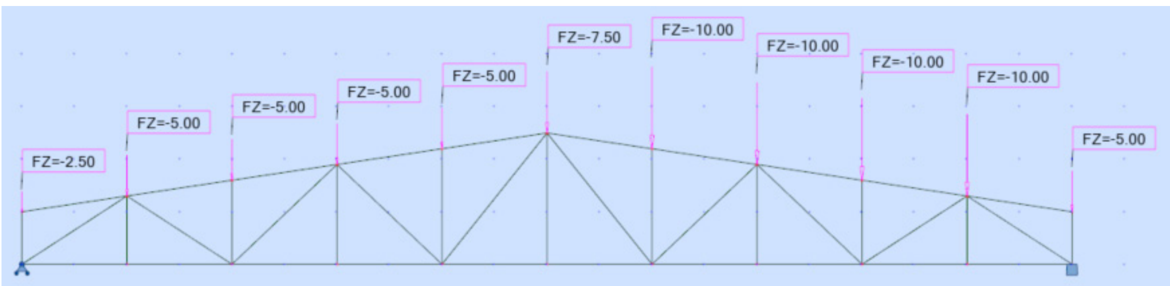

Fig. 4. Final geometry imported to robot structural analysis

Source: own work.

appropriate value of '*n*' in the case of the script executed (Fig. 2). The result *n*/2 is an odd number.

The initial part of the script began by giving parametric values in the code block node (Fig. 3). The following were defined: the number of truss fields, the distance between truss posts and the truss heights. The essence of the created algorithm is the ability to change the geometry of the truss by changing the listed parameters without additional modifications. Figure 4 presents the robot structural analysis visual representation of the generated structure with all loads and loads cases.

Figures 5 and 6 visually illustrate the transformative potential of parametric scripting in architectural design. Parametric scripting empowers designers to create intricate, adaptable geometries responsive to various parameters. This fosters design innovation, streamlines processes and enhances adaptability and sustainability through automated updates and modifications.

RESULTS AND DISCUSSION

The gathered loads from each case were applied to the structure. The calculations were performed using Robot Structural Analysis 2023.

The designed truss geometry modelling script allows changing the shape by changing parametric values. The presented algorithm includes truss heights, truss post spacing and the number of truss fields. In addition, it is possible to select the sections used in Robot Structural Analysis 2023 using the script.

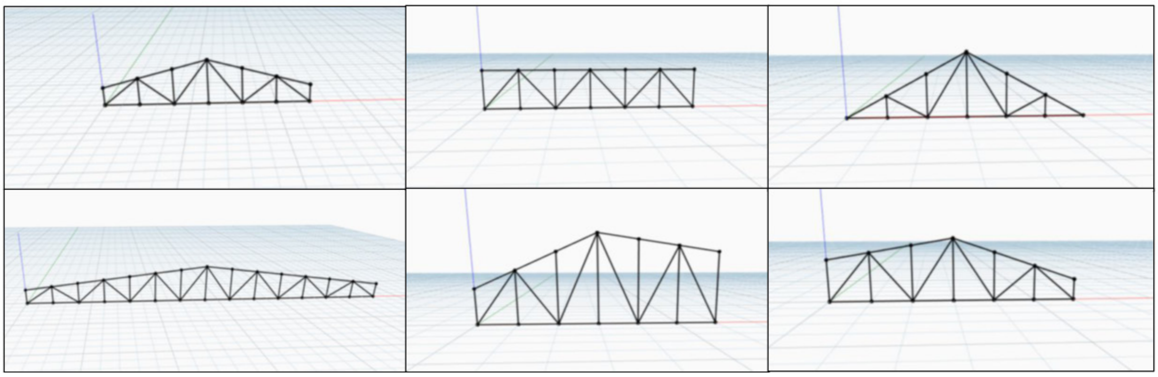

Fig. 5. Different cases created by changing the parameters of the script

Source: own work.

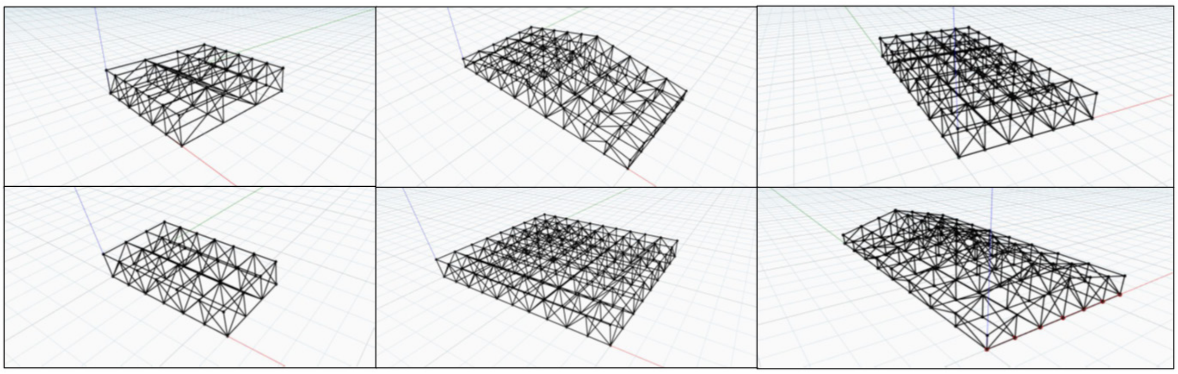

Fig. 6. Different cases created by changing the parameters and extending the script

Source: own work.

The analysed truss structure was created with the following parametric values: $n = 10$, $h_1 = 1$, $h_2 = 1$, $h_3 = 2.5$, $d = 2$.

Using Robot Structural Analysis 2023, static--strength calculations were made and sections were selected for the designed truss. Using the analysis in Robot, 246 combinations in ULS and 83 combinations in SLS were generated. Twenty-four truss elements were considered in the analysis, and sections were selected considering the ultimate limit state. In the case of the first element (bottom chord), case ULS189 was selected as the case of the most stressed element. An HD 360×196 section was selected to meet the given criteria.

For the first and second element, which form the top chord of the truss, the ultimate limit state was maintained for ULS189 and ULS192 using the HEB 220 section.

The posts and cross-braces of the truss were designed from TREC 80×80×8 pipes. All elements were made of S355 steel.

It should be added that in the case of the algorithm, the user is not limited to generating a single result. In the case of the presented script, there are other solutions that, despite the change of the truss geometry, are compatible with Robot Structural Analysis and Revit. The following section of this paper presents examples of truss geometries created by changing parametric variables.

The designed script can generate various types of 2D geometry; however, it is possible to extend the algorithm to create 3D geometry. The modelling of 3D elements from the already created geometry is possible by using, for example, translations by given sizes.

Using several nodes in the Dynamo script, the resulting truss was copied and shifted by a given distance. This step was repeated the desired number of times.

The introduction section of the text sets the stage by introducing the concept of parametric design and its relevance in architecture, especially in the context of digital tools and structural elements. It lays the foundation by explaining the use of parameters in design. The subsequent literature review section delves deeper into the topic, examining historical and contemporary instances of parametric design in architecture. It highlights how architects like Gaudi applied parametric principles to create innovative structures. This section provides theoretical and historical context to the discussion.

Towards the end of the introduction section, the text introduces the truss experiment as part of the broader conversation about tools that support parametric design. The truss experiment serves as a practical example of how parametric modelling tools can be applied to structural design, demonstrating the principles discussed in the previous sections.

The truss model aims to showcase the advantages and challenges of parametric design in structural engineering and architecture. It allows for the parametric manipulation of the truss's geometry by altering parameters such as the number of truss fields, the distance between truss posts and the truss heights. Through this experiment, one can explore how changes in these parameters impact the overall design and structural integrity.

The truss experiment functions as a case study, illustrating how parametric modelling can be used in the design of structural elements. It provides a platform for designers and engineers to iteratively test different configurations, optimising the design to meet specific requirements. Additionally, it underscores the potential benefits of parametric design in terms of efficiency and adaptability.

The designed script can generate various types of 2D geometry (Fig. 4). However, extending the algorithm to create 3D geometry is possible. The modelling of 3D elements from the already created geometry is possible by using, for example, translations by given sizes (Fig. 5).

Using several nodes in the Dynamo script, the resulting truss was copied and shifted by a given distance. This step was repeated the desired number of times.

The presented way made it possible to extend the script uncomplicatedly. The result is the creation of a parametric 3D geometry in which it is possible to change the spacing between the posts, the height of the posts, the number of fields and with further expansion of the script, the length of the grate in the direction of the y axis.

In the following section of the paper, different variants created by changing the parameters of the extended script are presented.

Parametric modelling supports the design process by enabling the creation of designs linked to adjustable parameters. These parameters act as variables governing the geometry and structure of a design. Instead of relying on intuition alone, parametric models offer a systematic and rule-based approach to design. They facilitate design by allowing for the manipulation and optimisation of design solutions according to specific rules and mathematical algorithms. This approach enables designers to explore various design alternatives, maintain consistency in design elements and efficiently respond to design challenges and changing project requirements. In essence, parametric modelling provides a structured framework that enhances creativity and problem-solving in the design process.

The presented parametric design of the truss structure differs significantly from the traditional one created only in Robot Structural Analysis 2023. The created script allows changes by altering a single parameter and their simultaneous implementation into the calculation program. In the presented parametric design, it is possible to change the geometry in terms of the spacing between the truss posts, the number of truss fields and the height of the truss. When using the Dynamo add-on and the algorithm presented here, it takes a negligible amount of time to make the change since it involves changing the value of the code block entry. Another significant advantage is that there is no need to model the structure from scratch in the Robot program. A typed change in the algorithm and running the script will automatically model the truss in the calculation software. Another advantage that encourages the user to use algorithms is that it saves time and promotes more frequent design changes.

Another advantage is the ability to add load cases and individual load values combined with the transparency of the Dynamo add-on. Using groups in the algorithm allows you to control the applied loads without switching case windows (as with Robot) and constantly view the applied values. An undoubted advantage is the ability to change the cross-sections used in individual parts of the structure. The converted algorithm uses three sections: top chord, bottom chord, posts and crossbeams. At any time, the script user can change the cross-section of a given element through the algorithm, which can be a significant time-saver in the case of complex structures. The presented script is extensive, but it is essential to note the versatility of the presented project. The paper includes nine sample geometries for which the script gives correct solutions. The generated trusses were created by making changes to the five parametric variables of the script. After running the script, each geometry was simultaneously generated in Robot with load cases prepared, loads applied supports used and cross-sections specified for each truss element. Thus, there is no need to model the elements from scratch in Robot, and changes are implemented when the script is run.

CONCLUSION

Parametricity is an exciting issue in both architecture and construction. It has inspired and led to unusual forms for many years. Algorithmic thinking is not limited by digital design tools and is considered its basis. An example is the early parametric work of architects such as Gaudi or Serrano. The development of parametricity aroused an increasing desire to optimise work and present new design opportunities. With the passage of time and the emergence of new iconic buildings, there was a desire among their creators to reach higher above traditional building-design thinking. This led to the beginning of the parametric period.

Parametric model control should be mentioned as an essential advantage. This control relates to the model's geometry, the amount of materials used, the layout and, taking into account the structural aspect, the model's strength. The occurring trend of using evolutionary algorithms in design activities is increasing – starting with evolutionary optimisation (EO) and distributed optimisation (PSO), it is common among authors to achieve better and faster performance of individual algorithms. The referenced scientific articles show new developments internationally by budding architects, which are used for optimisation worldwide. It proves that even architects without much design experience can realise more advanced analyses in a much shorter time compared to the previously referenced parameterisation pioneers.

Parametric design is mainly focused on architectural activities, but the subject is increasingly used in the construction industry. The presented parametric design of a truss highlights the advantages of the parametric design of structures, which are significantly superior to a traditional design made without the addition of a Dynamo. The presented solution in the project's initial phase may cause difficulties; however, it should be mentioned that despite the problems, an essential part of parametric design is the constant possibility of expanding and making changes to the design.

Further research in the field of parametric design should explore the practical implementation and integration of parametric modelling tools in architectural and construction projects to assess their real-world impact on design efficiency and creativity. Furthermore, exploring the potential for extending parametric design principles to other domains within construction, beyond truss structures, could provide valuable insights into the broader applicability of parametricity in the industry.

Authors' contributions

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

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

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WYKORZYSTANIE PROJEKTOWANIA GENERATYWNEGO DO OPTYMALIZACJI WIELKOŚCIOWEJ MAŁYCH FORM KONSTRUKCYJNYCH

STRESZCZENIE

W XXI wieku najbardziej zaawansowane metody cyfrowe umożliwiły projektowanie, analizę i wielokierunkową optymalizację konstrukcji na podstawie wielu parametrów. Algorytmy matematyczne, zdefiniowane według wymogów proporcjonalności, umożliwiają w oprogramowaniu stworzenie indywidualnego rozwiązania dla zadanych warunków brzegowych. Jest to szczególnie interesujące z punktu widzenia prefabrykacji i inżynierii materiałowej, którą obecnie coraz częściej cechuje idea postfordyzmu, czyli dążenia do unifikacji bez wykluczania twórczego poszukiwania indywidualnych rozwiązań. Badania przedstawione w artykule stanowią próbę odpowiedzi na pytanie, w jaki sposób projektowanie parametryczne kratownic prętowych można wdrożyć do optymalizacji elementów konstrukcyjnych. Metodologia polegała na wykorzystaniu narzędzi projektowania parametrycznego w celu stworzenia symetrycznego modelu kratownicy, oceny jej zalet i wad z uwzględnieniem różnych przypadków obciążeń. W podsumowaniu zawarto informacje o ewolucji projektowania parametrycznego, która nie tylko zrewolucjonizowała architekturę i budownictwo oraz zainspirowała powstanie niekonwencjonalnych form, lecz także ułatwiła optymalizację procesów projektowych, dostarczyła nowe możliwości projektowania oraz umożliwiła skuteczne sterowanie różnymi aspektami modelowania, co potwierdza jej nieocenioną rolę zarówno w architekturze, jak i budownictwie.

Słowa kluczowe: projektowanie algorytmiczne, produkcja cyfrowa, projektowanie generatywne, produktywność ICT, projektowanie interdyscyplinarne, projektowanie parametryczne, optymalizacja konstrukcyjna

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A COMPARATIVE STUDY OF SELECTED MODELS FOR EFFECTIVE THERMAL CONDUCTIVITY

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ABSTRACT

This paper conducts a comparative evaluation of 22 models focusing on the effective thermal conductivity of two-phase porous materials. Calculations were performed for each model across a range of solid-to--fluid thermal conductivity ratios, spanning from 1 to 15,000, and for two different porosities: 0.1 and 0.2. The study advocates the use of dimensionless charts that normalised solid thermal conductivity (k_s) and effective thermal conductivity (k_{ef}) concerning fluid thermal conductivity (k_f) for qualitative analysis. Employing this approach, the examined models were categorised into four fundamental groups. The latter portion of the paper compares selected models with experimental data. These experiments involved testing eight porous media samples in the form of packed steel bars, arranged in two configurations: staggered and in-line. The tests were conducted over a temperature range of 75–400°C, corresponding to k_s-to-k_f ratios ranging from 1,800 to 855. Various graphical representations were used to compare measurement data with model calculations. The findings indicate that the most accurate comparisons can be made using linear charts, which present absolute values of the k_{ef} coefficient in relation to the thermal conductivity of the solid phase.

Keywords: thermal conductivity analysis, porous materials, cellular materials, heat exchange

INTRODUCTION

Porous and cellular materials are composite structures that consist of a solid framework that houses voids filled primarily with gas or fluid. Within this category, materials featuring metals as the solid phase represent a significant subgroup. The concept of porous and cellular metals was first introduced in the early 1970s, and they have found successful applications across various industries – including aviation (Öchsner, Murch & Lemos, 2008) and space exploration (Vujayakumur, 2004).

A fundamental physical property of these materials is their effective thermal conductivity, denoted as k_{ef}. This parameter encapsulates the intricate interplay of heat transfer mechanisms, including conduction through the solid phase, conduction through the gas phase and radiation within the void spaces (Wei, Zhang & Yu, 2009). Determining the effective thermal conductivity of cellular and porous materials is essential for tasks such as thermal design and numerical simulations. Consequently, research focusing on k_{ef} is crucial for numerous practical applications.

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Several mathematical models have been developed to calculate k_{ef}. An important challenge in this field is comparing results obtained through different models. A widely accepted approach for this purpose is to normalise both the solid thermal conductivity (k_s) and effective thermal conductivity (k_{ef}) with respect to the thermal conductivity of the fluid (k_f), yielding dimensionless charts (Van Antverpen, du Toit & Rousseau, 2010). However, it is worth noting that drawing conclusions based solely on such diagrams can be misleading due to the use of logarithmic scales. This paper seeks to delve into these issues in greater depth. As a result, we present model-based computations in various formats. An essential aspect of our analysis involves comparing of model-derived k_{ef} values with our own results from experimental measurements.

MATERIAL AND METHODS

In this study, we examined 22 distinct effective thermal conductivity models. The presentation of these models is limited to their names. However, the complete mathematical equations and details regarding the methodology and assumptions used in their derivation can be found in the provided references. In Table 1, we list the models that were analysed in this study to assess effective thermal conductivity.

Table 1. Models examined for effective thermal conductivity

Name of the model	References
Parallel	Wang, Carson, North and Cleland (2006)
Series	
Maxwell Upper Bound	
Maxwell Lower Bound	
Effective Medium Theorem	
Horai	Horai (1991)
Beck	Beck and Beck (1965)
Chang	Chang (1982)
Assad	Assad (1995)
Woodside	Woodside and Messmer (1961)
Bruggeman	Abereshi, Goharshadi, Zebarjad, Fadafan and Youssefi (2010)
Miller Upper Bound	Miller (1969)
Miller Lower Bound	
Kunii–Smith	Kunii and Smith (1960)
Zehner–Schlunder	Zehner and Schlunder (1970)
Krupiczka	Krupiczka (1967)
Levy	Levy (1981)
Kopelman	Kopelman (1966)
Hill	Hill, Leitman and Sunderland (1967)
Rayleigh	Pietrak and Wiśniewski (2015)
Krischer	Krischer (1956)

Source: own work.

The Parallel and Series models represent the upper and lower limits of k_{ef} and serve as reference bounds for the other correlations. The models under consideration can be categorised into two main groups. The first group comprises rigid models, which are solely functions of thermal conductivities and porosity. The second group consists of flexible models, which include additional parameters. Notably, the flexible category encompasses two Miller models, the Kunii––Smith model and the Krischer model (Carson, Lovatt, Tanner & Cleland, 2006).

In calculating the k_{ef} coefficient, a thermal conductivity value of 0.0257 $W \cdot m^{-1} \cdot K^{-1}$ was adopted for k_f, representing the thermal conductivity of air. The value of k_s was varied across a range from 0.0257 to 386 $W \cdot m^{-1} \cdot K^{-1}$, with the upper limit corresponding to copper. Under these assumptions, the ratio of conductivity (k_s/k_f) was examined across a spectrum from 100 to 1.5×10^4. Calculations for each model were conducted for two distinct porosities, namely 0.1 and 0.2, representing granular media composed of cylindrical particles arranged in a staggered and in-line configuration, respectively.

As part of the analysis, a critical aspect involved comparing the model calculations with experimental results. To achieve this, we utilised measurements conducted on packed steel bar beds (as reported by Wyczółkowski in 2017). These beds represent two--phase granular media composed of steel and air. The examinations specifically concentrated on two distinct bar arrangements: staggered (with a porosity of 0.1) and in-line (with a porosity of 0.2).

The samples for each type of bed consisted of bars with varying diameters: 10, 20, 30 and 40 mm. Measurements were carried out for each sample over a temperature range spanning from 75° to 400°C.

RESULTS AND DISCUSSION

The calculated effective thermal conductivity values were initially presented in dimensionless logarithmic diagrams. For clarity, we have presented eight separate diagrams on each figure (Fig. 1 for porosity 0.1 and Fig. 2 for porosity 0.2). In each diagram, we have included results obtained for the boundary models, namely the Parallel and Series models, with the results of other models positioned in between. These diagrams effectively illustrate how the coefficient k_f changes for individual models based on variations in the k_s-to-k_f ratio. However, it is essential to note that data presented in this format primarily provides qualitative information. This makes it challenging to precisely determine the extent of differentiation between individual models.

To address this, we grouped the considered models into several categories. The first group, labelled 'Upper', consists of models closely resembling the Parallel model. This group was further subdivided into two subgroups: 'Upper A', encompassing models very similar to the Parallel model, including Maxwell UB, EMT, Bruggeman, Kopelman, Miller UB 1/9 and Krischer 0.0001, and 'Upper B', consisting of models that are less similar to the Parallel model, such as Horai, Levy, Hill, Miller UB 1/3 and Krischer 0.001.

The second group, termed 'Lower', comprises models with results closely resembling the Series model, particularly for which the conductivity ratio does not exceed 50 across the entire range of k_s. Models within this group include Maxwell LB, Woodside, Rayleigh and Miller LB 1/3.

The third group encompasses models with results in the dimensionless diagrams that exhibit profiles similar to the Series model. However, these models predict conductivity ratios close to or greater than 50 across the entire k_s range and are denoted as 'Mean'. This group includes Zehner–Schlunder, Miller LB 1/9, all Kunii-Smith models and Krischer 0.1.

The last group, termed 'Residual', includes models with results falling between the 'Upper' and 'Mean' models, represented by Beck, Assad, Krupiczka and Krischer 0.01. These categorisations help provide a structured framework for understanding the differences among the models.

Figure 1 presents dimensionless logarithmic diagrams illustrating the values of k_{ef} obtained for a porosity of 0.1 and, in Figure 2, for a porosity of 0.2. Each diagram within this figure showcases the variation in k_{ef} values across the examined models, with the Parallel and Series models as reference boundaries. These diagrams offer a qualitative representation of how individual models respond to changes in the k_s-to-k_f ratio. However, it's important to note that these charts primarily convey qualitative information. For a more precise understanding of the differences between the models, they were categorised into several groups (as discussed earlier).

New diagrams have been created to showcase the quantitative distinctions among individual models (see Figs 3 and 4). These diagrams portray variations in the k_{ef} coefficient concerning k_s, spanning from 25.7 to 257 $W \cdot m^{-1} \cdot K^{-1}$. The lower end of this range corresponds to high-alloy steel, while the upper limit represents pure aluminium. These diagrams are instrumental in providing a more precise understanding of the differences between the models.

For the models in the Upper A group, it was observed that an increase in porosity led to greater discrepancies between the results obtained by individual models. Within this group, the Kopelman model exhibited the closest similarity to the Parallel model, while the EMT and Bruggeman models were the least similar. Considerably greater variations were noticed within the Upper B group. The results of the Miller and Horai models remained unaffected by changes in porosity, whereas other models in this category demonstrated sensitivity to porosity variations. Among the Upper models, the Hill model was the closest to the upper bound, while the Levy model deviated the furthest from this boundary. What is common among all Upper models, except for Krischer, is that the k_{ef} values they predict increase as the thermal conductivity of the solid phase, k_s, increases. This suggests that solid-phase conduction is the primary mechanism of heat transfer in these models. Moreover, for all models in this category (except Krischer), the increase in the k_{ef} coefficient versus k_s is linear, and the discrepancies in results compared to the Parallel model do not intensify with

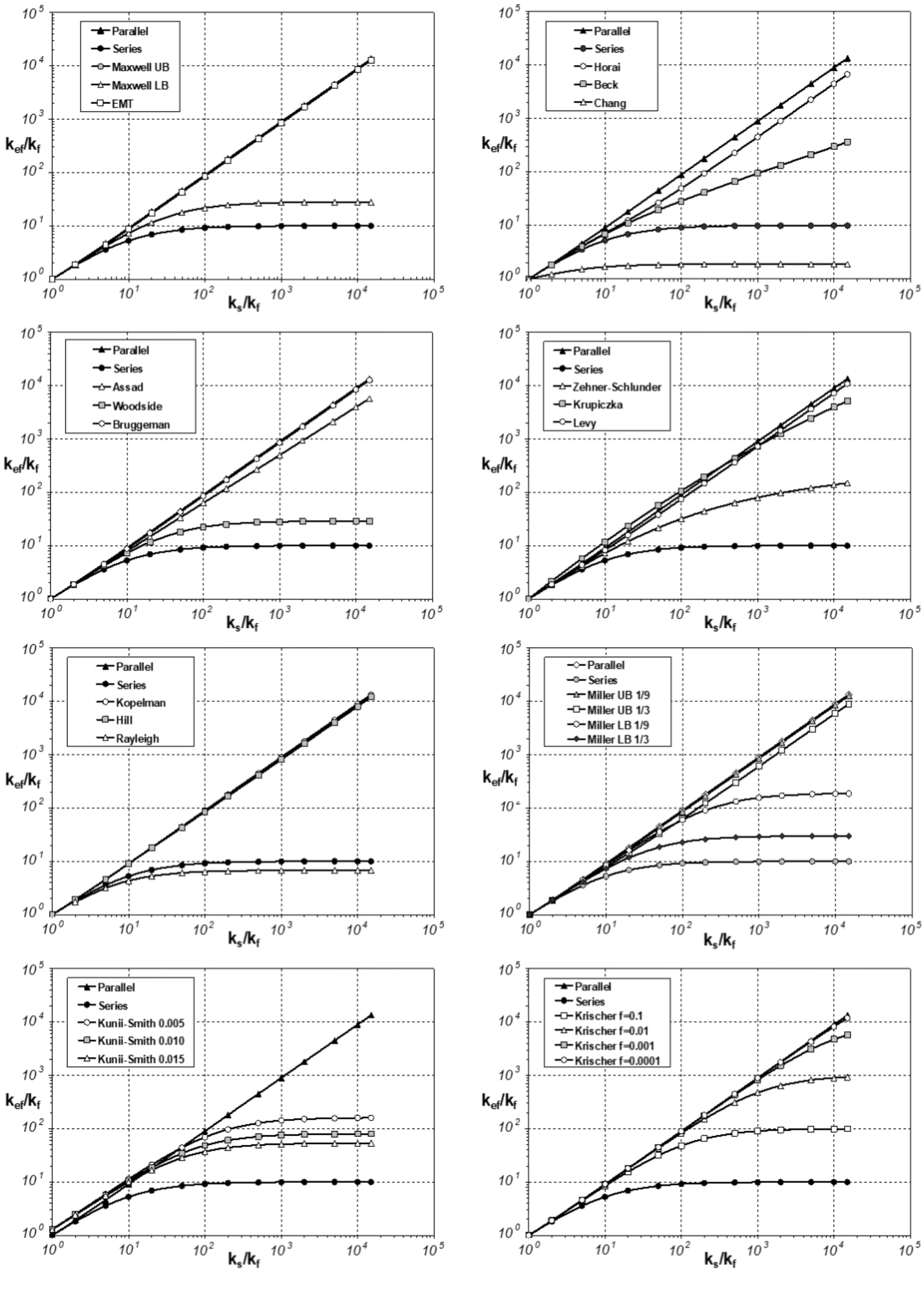

Fig. 1. Dimensionless logarithmic charts of effective thermal conductivity (k_{ef}) values for porosity 0.1

Source: own work.

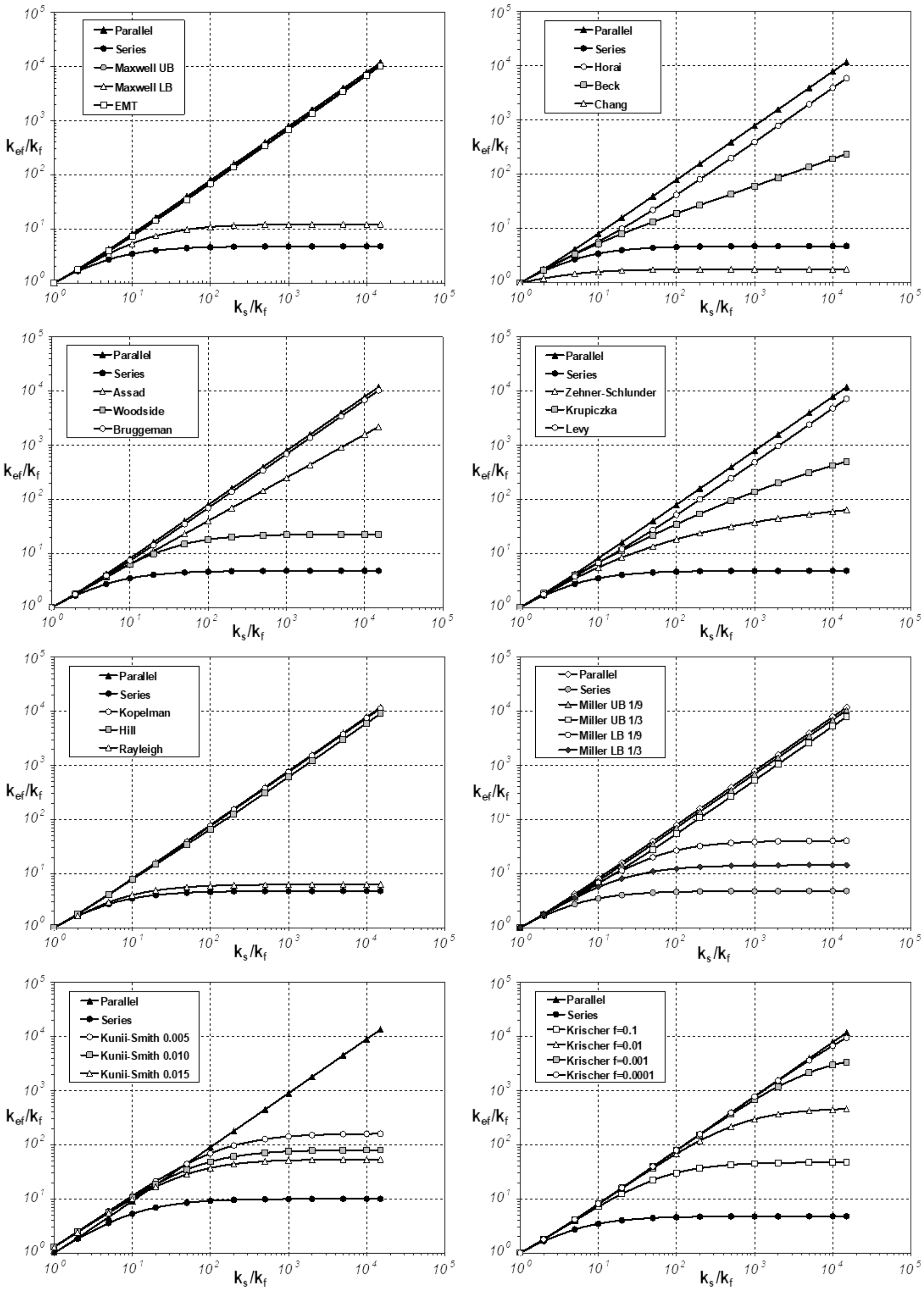

Fig. 2. Dimensionless logarithmic charts of effective thermal conductivity (k_{ef}) values for porosity 0.2

Source: own work.

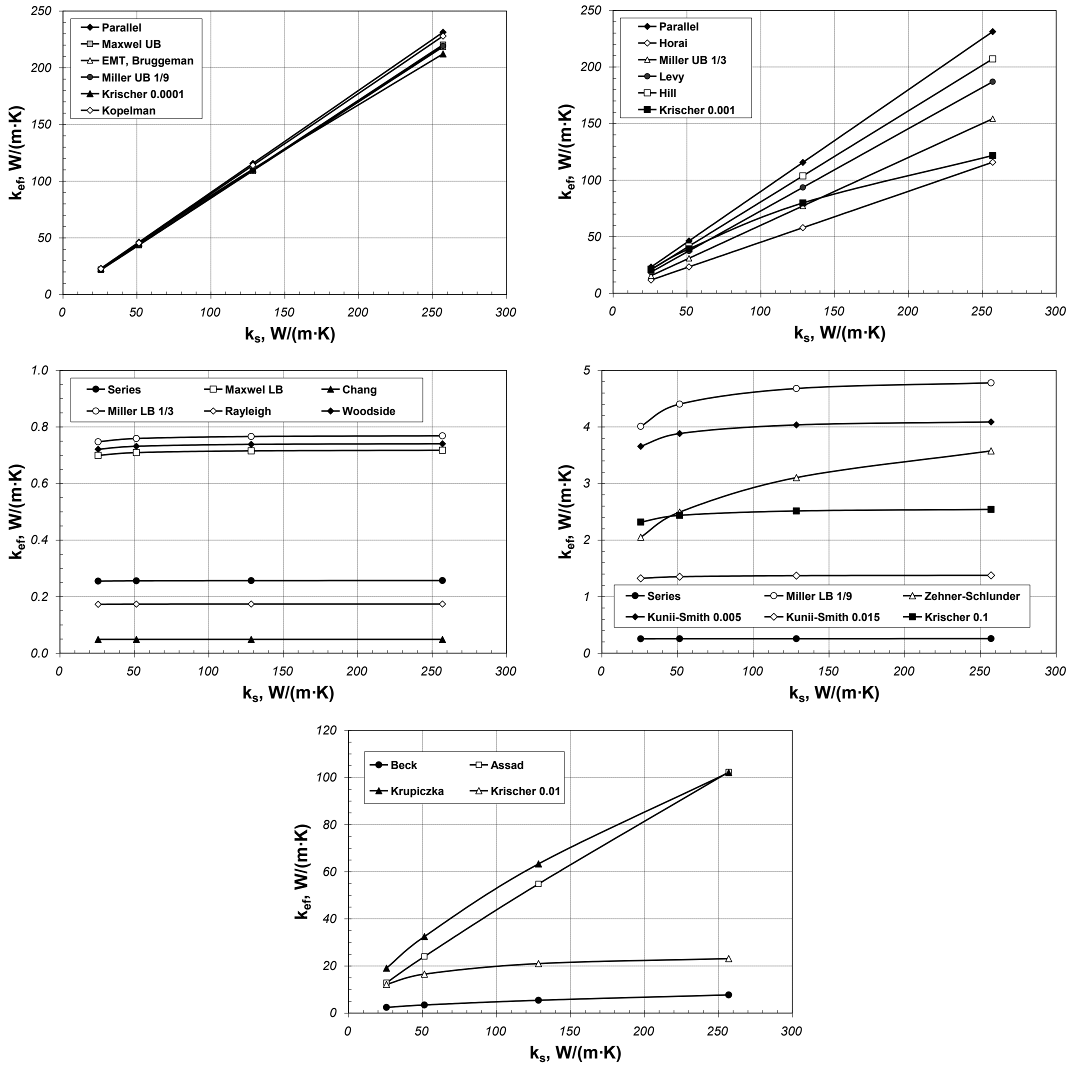

Fig. 3. Effective thermal conductivity (k_{ef}) versus normalised solid effective conductivity (k_s) calculation for porosity 0.1

Source: own work.

an increasing k_s. In the Krischer model, the increase in k_{ef} dynamics reduces with higher k_s values.

In the case of Lower models, the k_{ef} coefficient remained unchanged with varying k_s. This implies that these models primarily rely on fluid-phase conduction as the dominant heat transfer mechanism. Mean models, similarly to Lower models, respond to porosity changes but do not exhibit substantial variations as the thermal conductivity of the solid phase increases. However, one exception is the Zehner––Schlunder model, which responds to changes in k_s, particularly at low porosities.

Except for the Beck model, the results for the residual models exhibited a strong dependence on porosity, with the most significant effect observed among all the specified groups. Additionally, for all four models in this category, the k_{ef} coefficient increased as the thermal conductivity of the solid phase (k_s) rose. This indicates that solid-phase conduction the is primary heat transfer mechanism in these models.

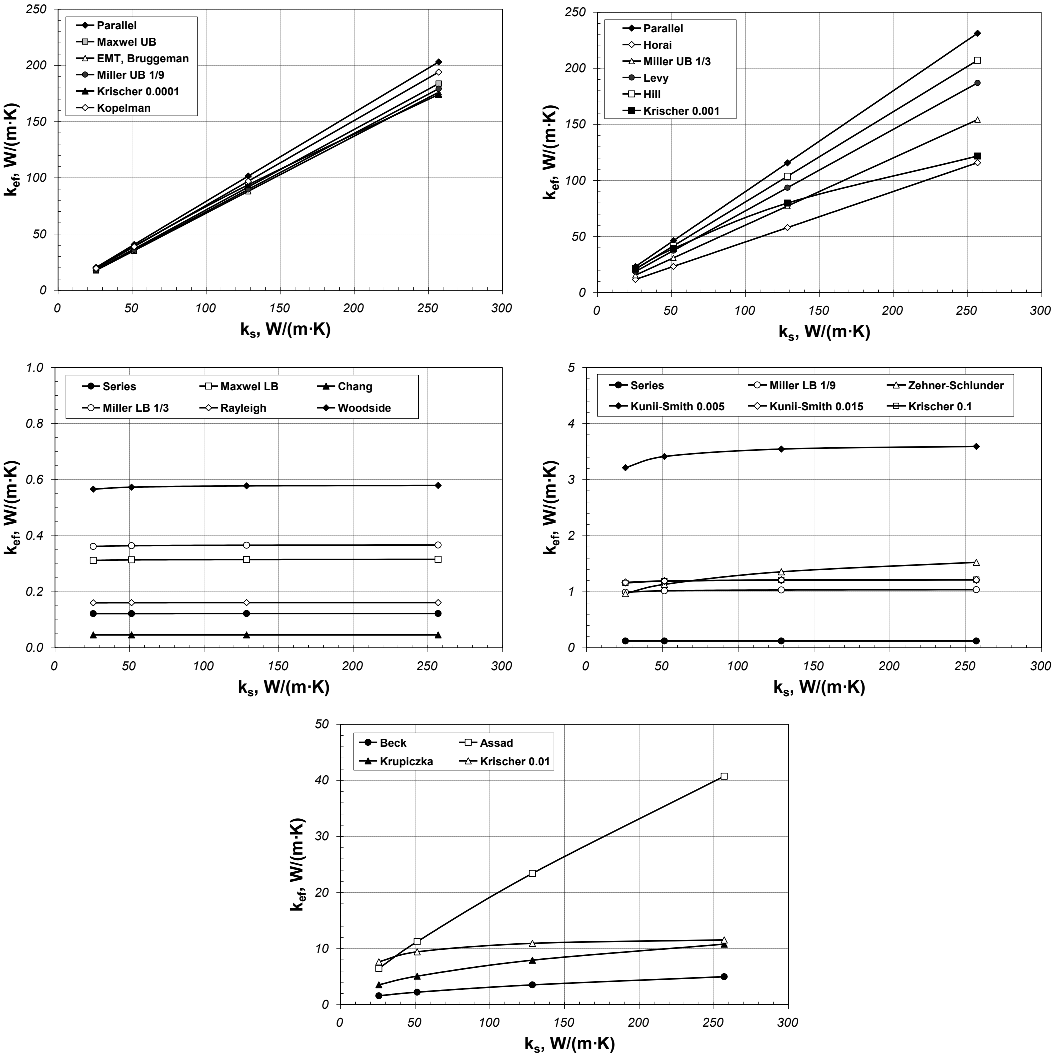

Fig. 4. Effective thermal conductivity (k_{ef}) versus normalised solid effective conductivity (k_s) calculation for porosity 0.2

Source: own work.

As previously mentioned, another essential analysis aspect involved comparing the model calculations with experimental results. The results of these measurements are presented in Figure 5, where Figure 5a pertains to staggered samples and Figure 5b pertains to in-line samples.

To facilitate the comparison of experimental data with model values of k_{ef}, additional calculations were necessary. These calculations required information about the coefficients k_s and k_f, which pertain to low-carbon steel and air for the bar beds. The variations in the k_s and k_f values with respect to temperature are described by the following relationships (Wyczółkowski, 2017):

$$k_s = 1.24 \cdot 10^{-8} t^3 - 3.26 \cdot 10^{-5} t^2 - 1.19 \cdot 10^{-2} t + 51.35, \quad (1)$$

$$k_f = -2.882 \cdot 10^{-8} t^2 + 8.051 \cdot 10^{-5} t + 0.02. \quad (2)$$

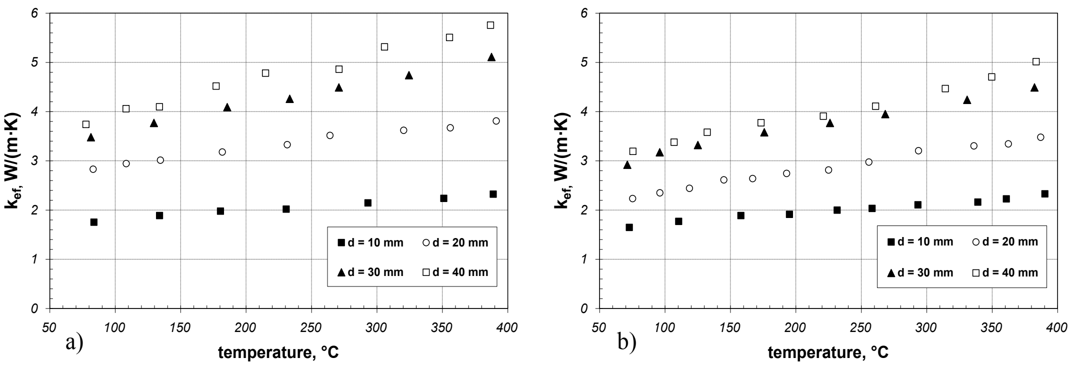

Fig. 5. Experimental results of effective thermal conductivity (k_{ef}): a – values for staggered samples; b – values for in-line samples

Source: own work.

Within the temperature range considered in the experimental investigations, the k_s-to-k_f ratio for the samples ranged from 856 to 1,681. For each sample, the changes in the k_{ef}-to-k_f ratio are presented as logarithmic diagrams, as shown in Figure 6a for staggered samples and Figure 7a for in-line samples.

It was observed that the results obtained for samples with a porosity of 0.1 closely resemble those of eight models: Maxwell LB, Beck, Woodside, Miller LB 1/3, all cases of Kunni–Smith, Zehner–Schlunder and Krischer 0.1. Moreover, the results obtained for samples with a porosity of 0.2 are akin to five models: Beck, all cases of Kunii–Smith, Zehner–Schlunder and Krischer 0.05. The values obtained for these models are presented in Figure 6b for staggered samples and Figure 7b for in-line samples.

Figures 8 and 9 display variations in the k_{ef} coefficient in dimensional form concerning k_s. Among all the presentation methods, this form is the most convenient for analysis. When considering the staggered beds, the best match is observed between the 20-millimetre sample and the Zehner–Schlunder model. In the case of in-line beds, the most accurate alignment is found between the 20-millimetre sample and the Kunii–Smith 0.1 model.

Based on the results of the examinations, it is evident that linear diagrams with data presented in

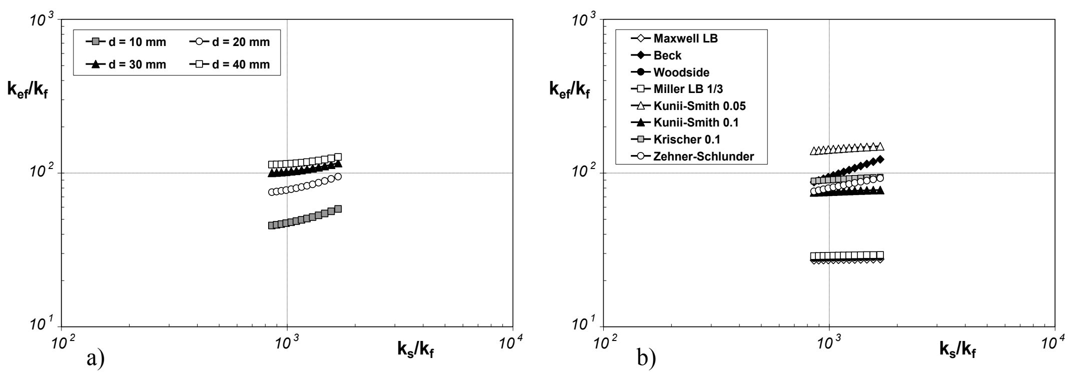

Fig. 6. Comparison of values of effective thermal conductivity (k_{ef}) in dimensionless logarithmic charts for porosity 0.1: a – experimental data; b – model results

Source: own work.

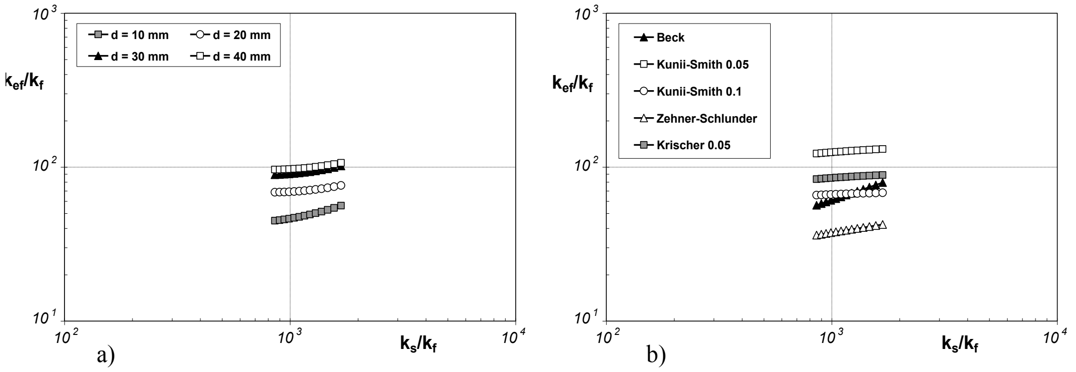

Fig. 7. Comparison of values of effective thermal conductivity (k_{ef}) in dimensionless logarithmic charts for porosity 0.2: a – experimental data; b – model results

Source: own work.

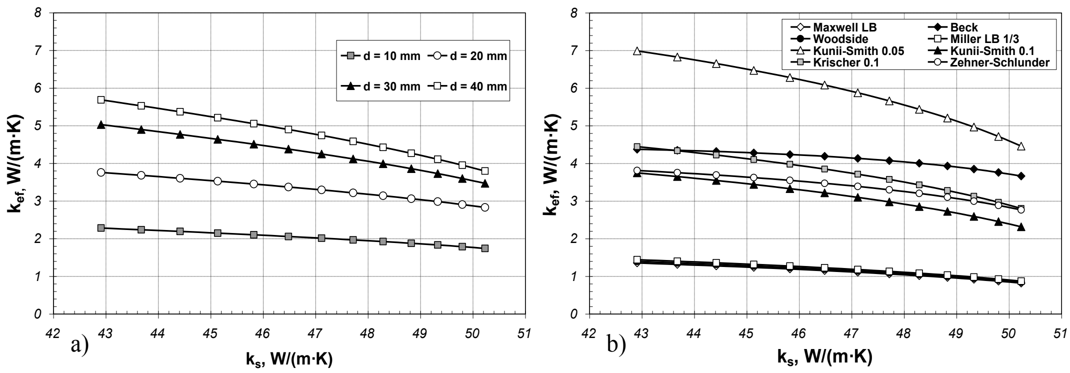

Fig. 8. Comparison of values of effective thermal conductivity (k_{ef}) in dimensional form (k_{ef} versus k_s) in the linear charts for porosity 0.1: a – experimental data; b – model results

Source: own work.

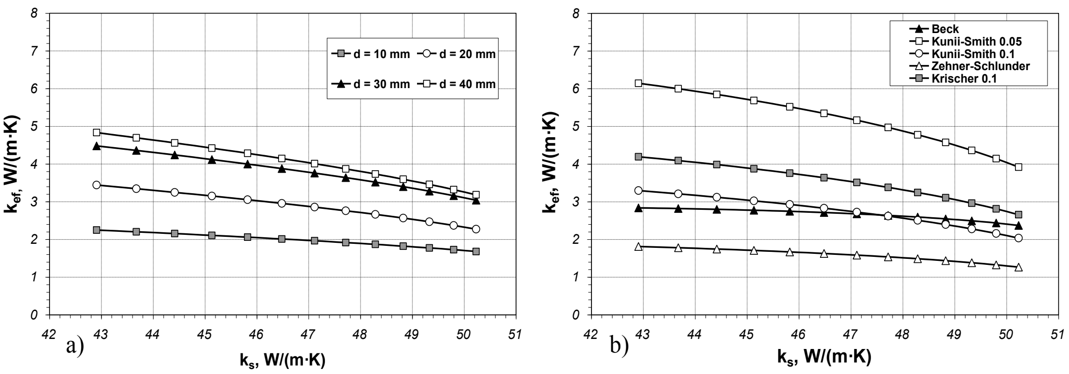

Fig. 9. Comparison of values of effective thermal conductivity (k_{ef}) in dimensional form (k_{ef} versus k_s) in the linear charts for porosity 0.2: a – experimental data; b – model results

Source: own work.

dimensional form are the most convenient for conducting comparative analyses of effective thermal conductivity. This approach is particularly effective when the analysed values of k_{ef}, k_s and k_f change over relatively smaller ranges. In instances where these values cover larger or more extensive ranges, using of logarithmic scales becomes necessary.

CONCLUSIONS

The comparison of various models of effective thermal conductivity is a significant concern within the field of thermophysics of porous media. This paper has provided a comprehensive analysis of 22 computational models for this parameter. It was evident that logarithmic dimensionless diagrams should primarily be used for qualitative comparisons. Comparing results obtained from models with experimental data can be particularly challenging and less transparent. Other types of diagrams should be employed to perform quantitative comparisons between specific models or with experimental data.

The suitability of using linear diagrams depends on the range of changes in the coefficients k_{ef}, k_s and k_f for the materials in question. Linear scales are preferable when these ranges are not excessively wide. However, when dealing with extended ranges, it is advisable to create several separate charts for narrower ranges of changes in these coefficients. For the most accurate comparisons, linear diagrams should be employed as they present changes in the absolute values of effective thermal conductivity as functions of thermal conductivity – k_s or k_f.

Authors' contributions

Conceptualisation: R.W., S.A. and V.B.; methodology: R.W and G.V.; validation: S.A. and V.B.; formal analysis: R.W. and G.V; investigation: R.W and V.B.; writing – original draft preparation: R.W. and S.A.; writing – review and editing: V.B. and G.V.; visualisation: V.B and G.V.; supervision: S.A and R.W.

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

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ANALIZA PORÓWNAWCZA WYBRANYCH MODELI PRZEWODNICTWA CIEPLNEGO

STRESZCZENIE

W niniejszej pracy przeprowadzono analizę porównawczą 22 modeli skoncentrowanych na efektywnym przewodnictwie cieplnym dwufazowych materiałów porowatych. Obliczenia zostały wykonane dla każdego modelu w zakresie stosunku przewodnictwa cieplnego ciała stałego do płynu (wahającego się od 1 do 15 000) oraz dla dwóch różnych porowatości (0,1 i 0,2). Badanie prezentuje wykorzystanie bezwymiarowych wykresów normalizujących przewodnictwo cieplne ciała stałego (k_s) oraz efektywne przewodnictwo cieplne (k_{ef}) w odniesieniu do przewodnictwa cieplnego płynu (k_f) do analizy jakościowej. Dzięki temu podejściu modele zostały zbadane i sklasyfikowane w cztery podstawowe grupy. W drugiej części pracy porównano wybrane modele z danymi eksperymentalnymi. Eksperymenty obejmowały testowanie ośmiu próbek materiałów porowatych w postaci upakowanych prętów stalowych, ułożonych w dwóch konfiguracjach: przesuniętej i równoległej. Testy przeprowadzono w zakresie temperatury od 75° do 400°C, co odpowiadało stosunkom k_s do k_f w przedziale od 1800 do 855. Do porównywania danych pomiarowych z obliczeniami modelu wykorzystano różne rodzaje reprezentacji graficznych. Wyniki wskazują, że najbardziej dokładne porównania można przeprowadzić za pomocą wykresów liniowych, które prezentują bezwzględne wartości współczynnika k_{ef} w odniesieniu do przewodnictwa cieplnego fazy stałej.

Słowa kluczowe: analiza przewodnictwa cieplnego, materiały porowate, materiały komórkowe, wymiana ciepła

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REVIEW PAPER

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WHY DO CHICAGO BUILDINGS NOT RETROFIT?

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ABSTRACT

Retrofitting buildings undeniably offers opportunities to lower energy consumption and greenhouse gas emissions. However, choosing particular retrofit techniques is complex and needs planning. Several techniques exist for modifying buildings to use nearly zero energy. Chicago is world-famous for its downtown skyscrapers, neighbourhood bungalows and leafy suburbs. Still, behind their façades, Chicago-area buildings conceal an embarrassing and expensive reality: they use too much energy. By strategically combining available resources and existing knowledge, the Chicago area can make its physical structure more energy efficient, bringing environmental and economic benefits to the eight million people in this region. Therefore, the main focus of this study is to explore pertinent solutions, analyse the impact of such solutions on building energy efficiency and suggest renewable energy technologies. Extensive research involving numerical simulations or experiments is necessary to assess the feasibility of implementing these techniques in the specific climatic conditions of Chicago.

Keywords: decarbonisation, carbon dioxide emission, climatic strategies, retrofitting, Chicago

INTRODUCTION

In the 21st century, finding ways to minimise the carbon footprint in the construction industry has emerged as a key focus within the realm of modern sustainable interdisciplinary design. Rapidly developing countries are placing ever-higher legal requirements on the designers of new buildings in terms of the materials and construction technologies used. The question of existing buildings and how to make them less carbon-intensive and more comfortable for their occupants is increasingly beginning to be raised. In the United States, buildings are typically responsible for 40% of all carbon emissions – that figure rises to 70% in the city of Chicago. The transportation footprint is relatively modest, which contributes to this imbalance. However, like many older cities, Chicago's buildings frequently have out-of-date, inefficient systems that result in high energy loads. So, why do building owners not undertake any retrofitting measures to improve the quality of the building?

There is an enormous environmental problem in today's world. Designers, lawmakers and users must start undoing the harm done to the earth since the Second Industrial Revolution. The undeniable development brought to the world by the changes brought about by mass production on assembly lines and access to electricity has also led to greater exploitation of natural resources and littering of the urbanised environment with waste and greenhouse gases (Filho et al., 2023). There is now an increased awareness among producers of goods and designers and users of the carbon footprint of products and buildings (PCF – product carbon footprint). The sectors still generating the most significant carbon footprint are the construction sector and transport. In 2002, The 2030 Challenge's scientists

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estimated that 10 years of global reductions in greenhouse gas emissions are needed to avoid catastrophic climate change (Intergovernmental Panel on Climate Change [IPCC], 2021). Chicago created the Chicago Climate Action Plan in 2008 to address these problems. Today, designers know that progressing sustainably calls for more than just creating new, energy-efficient structures or increasing the number of hybrid vehicles on our road. There is an urgent need to drastically modify the current metropolis' landscape, changing how it looks and functions. Proper integration between a city's components is necessary for an urban ecosystem (City of Chicago Department of Environment, Parzen, Urban Sustainability Associates & The Center for Neighborhood Technology The City of Chicago Department of Environment, 2009). Smart energy systems depend on smart infrastructure development, just as smart buildings depend on smart transportation networks. Decarbonisation aims to make cities healthier, more sustainable and more habitable by enhancing the performance of all significant metropolitan systems.

Several buildings in the Chicagoland area have already undergone retrofitting. The energy efficiency of the buildings, landmarks and residences that make up Chicago is essential to creating a thriving, climate-resilient and sustainable city. Although climate efforts and new building rules are critical first steps toward achieving net zero emissions in Chicago, retrofits are the most crucial component in addressing one of the city's largest greenhouse gas emitters. For property owners throughout the city, building retrofits are vital for three reasons: the weather in Chicago; subterranean climate change and cost savings to improve user comfort and building efficiency. The paper focuses on the analysis of selected buildings in Chicago, and results in the identification of key factors (KF) contributing to the lack of retrofitting.

LITERATURE REVIEW

Law regulations

In the United States, buildings produce an average of 40% or more of the nation's carbon emissions – that percentage increases to 70% in Chicago. Commercial space in downtown Chicago takes up 90% of land use, which is responsible for 97% of carbon dioxide emissions. The Chicago Loop, in contrast, is mainly devoid of residential space and the services and infrastructure that many homeowners appreciate in their communities (e.g. grocery stores, daycare centres, parks and schools). This pushes people who work there to look for adequate housing and living spaces elsewhere in the city. As new technology has become commonplace in our daily lives, energy consumption in the United States (and, consequently, in Chicago) has substantially increased over the previous few decades, significantly surpassing population growth. While emerging technologies have put more stress on the ageing infrastructure, they also provide new opportunities to boost energy, information intelligence and distribution efficiency by creating new infrastructure intelligence (IPPC, 2021).

Building owners are encouraged by the voluntary Retrofit Chicago initiative to commit to cutting energy use by 20% over five years. Retrofit Chicago, established in 2012, has expanded from 12 to over 75 buildings, totalling more than 50 million square feet. The programme produces custom energy road maps for building owners to explore routes in order to cut energy use and increase annual savings. In 2018, Chicago officials estimated the programme had reduced emissions by 70,000 mt and saved 90 million kWh annually based on energy reporting by building owners. The city is looking for strategies to broaden engagement outside of the downtown area so that additional buildings can join in and take advantage of the pooled knowledge and resources.

Passed in 2013, the Chicago Energy Benchmarking Ordinance requires residential, commercial and institutional buildings over 50,000 square feet to report energy consumption annually. The programme aims to empower building owners and renters to make knowledgeable decisions about energy usage and promote energy efficiency. It also gives the city information it can use to focus programme resources more effectively. The 2019 Chicago Energy Benchmarking Report highlighted nearly $74 million in savings from energy reductions and its highest compliance rate (at 91%) of buildings covered under the ordinance. Furthermore, the new Chicago Energy Rating System requires building owners to display their energy performance to the public through a placard. Chicago was the first American city to require this level of public transparency for energy use. The Illinois Climate and Equitable Jobs Act (CEJA) was passed in September 2021 by the Illinois State Legislature. The CEJA sets Illinois on a path to 100% clean energy by 2050 and 100% carbon-free power by 2045. Beyond renewable energy build-out, the CEJA also commits to holding utilities accountable, creating an equitable clean energy future for all, ensuring affordability of energy bills, assisting the transition of fossil fuel communities and creating good-paying carbon-free jobs. Stand-out actions include an annual $80 million commitment to workforce and contractor development in equity-focused communities, minimum diversity and equity requirements for renewable energy projects, ending formula rates, a $40 million grant programme for fossil fuel communities in transition and an annual $80 million for electric transportation projects (Chicago, 2020).

The International Code Council (ICC) has approved the 2021 International Energy Conservation Code (IECC), which achieved the biggest energy efficiency gains in the past decade by updating requirements for insulation, lighting and water the 2021 IECC as part of the Chicago Energy Transformation Code in 2022. Under state law, Chicago can also consider a "Stretch Energy Code" starting in 2024. Regularly scheduled updates to the Chicago construction codes, based on model codes from the ICC and others, also provide opportunities to facilitate and promote building decarbonisation (City of Chicago, 2022).

The City of Chicago is dedicated to a building decarbonisation strategy that develops an equity-focused building emission reduction strategy that lessens financial burdens on residents and businesses through energy efficiency, renewable energy, electrification and innovation in new construction. This strategy is a component of the Green Recovery Agenda. To direct the creation of a collection of implementable building decarbonisation policies and programme recommendations, the City of Chicago established a Building Decarbonization Project' team in 2020. The Working Group is made up of participants from the private, public, and non-profit sectors, including experts in sustainability, architects and designers, workforce development organisations, builders and developers, building managers and operators, small businesses, community organisations, utilities, environmental justice and advocacy groups, youth groups focusing on climate change, labour unions, and universities. The policy development process included four phases: best practices research, extensive stakeholder engagement, policy development working group, and ongoing policy development and implementation. The working group identified numerous pressing issues that must be resolved in the upcoming years to decarbonise Chicago's building stock. Financial incentives to reduce carbon emissions in buildings are generally lacking. Most financial aid is funded through grants and cannot be scaled to meet changing needs; therefore, it is necessary to identify funding sources for decarbonisation initiatives in all buildings (City of Chicago, 2023).

Decarbonisation strategies

There are substantial information gaps regarding how to decarbonise buildings. A crucial option, building electrification, is poorly understood by the general public, and information is not easily available (Das & Ghosh, 2023). Additionally, there is a dearth of knowledge regarding utility programmes, rebates, retrofits and energy efficiency advantages (Sareen et al., 2023). Even though most people know about energy efficiency and renewable energy sources, there is still a need to address this because of the lack of adoption. Creating a communicative network of players that can develop, pilot and scale decarbonisation initiatives throughout the city is tough. There is a limited workforce to achieve the retrofits needed at scale. Among their other priorities, city authorities' capacity to quickly adopt decarbonisation programmes and offer citywide support is likewise constrained. To assist community participation and household energy transitions, building capacity will be necessary for non-profits, community-based groups and other non--profit organisations. This will be crucial for reducing energy use and costs in older and smaller residential homes that require retrofitting. The city, commercial enterprises, housing providers and industrial operations are examples of large institutions facing new problems in managing innovation ambiguities, shifting power dynamics and developing new drivers for inclusive economic growth. The benefits of building decarbonisation must be concentrated in frontline areas where residents and business owners who stand to gain the most from improvements must have access to the resources they need to engage in and finish projects effectively.

One of the country's most well-known and diverse skylines is that of Chicago. According to legend, this is where the skyscraper was erected in the years following the Great Fire of 1871. Architectural periods have been used to group buildings in Chicago based on their materials, scale, plan and aesthetic expression; however, to properly establish energy reduction plans, buildings must finally be classed according to their energy era and general performance readiness.

The Chicago Central Area Decarbonization Plan attempts to make a dynamic urban environment while lowering downtown Chicago's carbon emissions (Table 1). This is not a checklist, in contrast to other plans. It takes a comprehensive approach to improving the social, economic and environmental facets of city life in Chicago. The plan sets itself apart from other city plans by emphasising an integrated strategy for problem-solving. The analysis does not only arrive at a reduction number derived from a given set of applicable assumptions; instead, it analyses all the carbon sources typical of the urban condition. The plan establishes a framework for preserving the metropolitan core's economic and cultural vitality regarding energy and carbon. The assumption that growth may continue without having a detrimental environmental impact

Table 1. Retrofitting solutions in public buildings decarbonisation

Retrofitting solution	Description
Building envelopes	Building design has evolved significantly as a result of energy codes. Architects and engineers must constantly consider the behaviour of modern buildings concerning the environmental effect and energy needs. Demand for high-performance buildings is growing among owners and occupants. With the help of technology that maximises human comfort, buildings are gradually rediscovering their connection to the outside world.
Vertical transportation systems	Between 2% and 10% of the energy in a typical downtown building can be accounted for by the energy used by lifts and escalators. This is dependent on the size, number and function of the building, mainly the frequency and volume of lift activity. Although standard vertical transportation equipment has improved efficiency by around 50%, many outdated systems are still in use. Additionally, new technologies have been created to enhance lift systems by utilising digital controls to reduce the number of trips.
Lighting systems	Lighting systems have significantly improved compared to the original gas lamps in Chicago's early buildings. The ideal amount of daylight for the human eye can be used to build and automatically operate daylight lighting systems. However, a lot of modern structures have excessive lighting. The required lighting density at the time was estimated to be up to five times higher than what is typical today. The building was heated in part with the aid of lights.
Equipment or plug load	The electricity required for anything that must be plugged into an electrical outlet can be most easily understood as the equipment load in a building. While other building loads (such as lighting and envelope) have declined over time, plug loads have increased – particularly since the 1980s when computers were used extensively. The use of Energy Star-rated (or superior) equipment and automatic shutdown are two actions that can be implemented right away to lessen equipment loads. As electronic equipment develops and uses less energy, future technologies can further lower these burdens.
Green roofs and roof insulation	While roof insulation and low albedo or green roofs remain essential for mitigating the urban heat island effect in Chicago's downtown area, the impact is noteworthy despite buildings usually having a relatively small proportion of roof area. This effect is especially pronounced with older, dark-coloured roofs, which can reach temperatures of around 200 F in the summer. Additionally, green roofs play a crucial role in capturing stormwater runoff, contributing to reduced carbon emissions by eliminating the need for water treatment.
Energy sources	Assessing carbon emissions in buildings is impossible without considering the source of a building's energy. The energy that leaves power plants is lost in large amounts as it passes over the electricity grid. Peak energy demand has an impact on costs as well as the amount of energy coming from coal-fired power plants. Buildings can reduce their contribution to carbon emissions by managing and storing energy to lessen these peaks. While renewable on-site generating enables buildings to operate carbon-free, on-site energy generation can also cut transmission losses.

is essential to the viability of cities and urban living. Cities may become hubs for healthy, diverse lifestyles with little impact on the environment thanks to decarbonisation (Chicago, & Building Decarbonization Policy Working Group, 2022).

PUBLIC BUILDINGS TYPOLOGY IN CHICAGO CITY CENTRE

Numerous helpful comparisons can be made based on a building's energy era due to the historical evolution of technology in buildings and how structures have been used over time (Table 2).

Heritage buildings are the first category, comprising all buildings between roughly 1880 and 1945. Although these structures span a considerable amount of time, they all share a few fundamental characteristics like their construction type (usually masonry, stone or terra cotta with punched windows) and their utilisation of natural light and ventilation as intended when they were first built. Mid-century modern architecture is the second category.

Mid-century modern buildings comprise structures built between 1945 and 1975. A revolution in architecture took place after World War II, giving rise to a new breed of high-rise skyscrapers made of glass and steel and intensively illuminated. To make mainly glass elevations, curtain walls were created. The building loads caused by these significant amounts of glass and complex lighting systems might be mitigated thanks to more sophisticated HVAC systems. However, the drawback of these architectural advancements was a dramatic rise in building energy consumption. The 1973 OPEC oil embargo not only led to tighter fuel-efficiency regulations for cars, but it also raised people's awareness of how much energy is consumed in buildings. It encouraged increased investment in the initial cost of building energy-saving technologies. Large buildings constructed after 1975 frequently incorporated energy-saving technology, including insulated glass, variable volume air systems and solar films or coatings to lower energy loads and operating costs. These post-energy-crisis buildings fall into structures constructed between roughly 1975 and 2000. The last group of buildings are the energy-conscious buildings that were built between 2000 and the present during the current global drive toward energy efficiency. The Chicago Energy Code was adopted in 2001, coinciding with the rising popularity of LEED and other green standards.

Heritage: 1880–1945

Due to their short lease spans and substantial thermal mass for heat absorption, heritage buildings offer excellent options for natural ventilation, daylighting and heat absorption. However, many of these structures have not benefited fully from advancements in building technology over time. Sometimes a building's designation as a landmark will prevent it from getting full sustainable improvements.

Mid-century modern: 1945–1975

Due to the invention of curtain walls, modern structures frequently have a lot of glass. Technology during this time altered how structures were constructed. Artificial interior control has essentially replaced using the natural environment for heating, cooling and lighting. Due to changes in how offices are used, substantial HVAC systems and dense lighting became standard. Building construction was accelerated by mass manufacture, which also decreased costs and enhanced adaptability.

Post energy crisis: 1975–2000

The 1970s energy crisis had an impact on building construction methods. Insulating glass, heat-gain-reduction solar coatings, more effective HVAC systems and less lighting were all developed for high-rise structures. However, internal plug loads in buildings rose as computers advanced.

Energy consciousness: 2000–present

Building design has undergone a significant change as a result of energy codes. Architects and engineers nowadays must maintain a constant understanding of how building behaviour relates to environmental effects and energy needs. High-performance buildings are starting to be in demand from owners and renters. Slowly but surely, buildings are rediscovering their connection to the outside world – now balanced with technology that maximises human comfort.

Table 2. Public buildings in Chicago City Architectural description based on the chosen timeline

Specification	Timeline			
	Heritage (1880–1945)	Mid-century modern (1945–1975)	Post energy crisis (1975–2000)	Energy consciousness (2000–present)
Typical exterior wall materials	brick, stone, terra cotta (uninsulated)	stone, aluminium, steel, and other curtain wall systems, concrete	Systems for curtain walls: aluminium, stone and concrete. Mirrored or dark-tinted insulating glass was used until the 1990s. Clearer glass with low-E coatings from 1990 to 2000, 60–80% is glass. The implementation of thermal breaks.	Curtain wall systems: aluminium, stone, concrete. Insulated glass with low-E coatings is the industry standard in the United States. As energy codes become stricter, glass percentages become lower. Triple-glazing and double-skinned walls are introduced.
Typical exterior wall technology	structural steel and reinforced concrete	Most curtain walls were constructed before thermal breaks were developed, and most glass is single pane because insulating units were still in the early stages of development. Between 50 and 80% of it is glass.	steel, concrete, composite	concrete-steel composite
Windows	Double-hung windows with single-pane, clear glass. Glass percentage: 25–50%	Windows typically have transparent glass with manual shading systems and are slightly tinted (green, grey or bronze).	–	–
Ventilation systems	The HVAC system has generally been retrofitted or completely replaced over the years, especially for buildings older than 1930. Therefore, many mechanical systems exist in these buildings, from radiators to fan coil units to variable-volume overhead systems. Often, systems do not operate optimally because of changes over the years. Cooling systems have likely been added to the original building as air conditioning was not widely used before 1950. Many heritage buildings have opportunities for natural ventilation from short lease spans or light wells, but sometimes these have been covered over. Some buildings use district heating and cooling due to a lack of plant capacity. Others have large rooftop units added.	Mechanical systems often have perimeter induction or fan coil units that supply ducted systems with interior air. The conventional internal system is a constant electric reheat. Nowadays, it has mostly been replaced in many buildings by a variable volume system, which is more efficient. Although many mechanical plants have been converted for variable volume and economiser cycles, they were also originally constant volumes.	Tan coil or induction units along the periphery with ducted variable volume systems for the interior air. As less heating was required along the outer glass walls, loads fell. Variable equipment started to be used in mechanical facilities.	The VAV or tan coil systems with less perimeter heat are needed for better envelope performance. Use economiser cycles, variable frequency pumps, drives, and digital controls.

Electricity and lightning	Opportunities exist for natural light through short lease spans and light wells – especially in the oldest buildings. Buildings that did not initially have electric lighting have been retrofitted. However, early lighting retrofits typically have fewer lights than the over-lit buildings from the 1950s through the 1970s. Therefore, lighting and electrical loads in older buildings often consume less energy than in later buildings.	Buildings were planned with heat by light in mind, and lighting density in the middle of the 20th century was frequently as high as 5 W per square feet. It was discovered over time, with the advancement of computers, that these high levels were not required and that using the HVAC system for heating was more effective. Therefore, lighting density was frequently decreased during later tenant fit-outs. Introducing new technologies led to increased equipment loads (also known as plug loads).	Lighting steadily reduced from 1970s levels as heat-by-light incentives were phased out. Partial or complete retrofits/de-lamping may have decreased lighting loads. With the development of computers, office space became much more energy-intensive in terms of plug loads. This often caused overall electrical energy use, especially in office buildings and trading floors, to increase sharply.	Lighting levels were reduced to meet energy codes and LEED. Natural daylight and light sensors are the industry standard to meet energy guidelines. New technologies such as compact fluorescent lighting and LEDs are becoming more common. Plug loads remain high, but more efficient equipment is being developed to save energy.
Typical layout	Shallow lease spans and narrow floor plates or large floor plates with one or more light wells.	Typical layout – 30,000–50,000 square feet floor plans with a central core are very large.	Large floor plates of 30,000–50,000 square feet with a central core.	Large floorplates remain typical for office space, but more attention is paid to orientation, and shallower lease spans for natural light.
Site and surroundings	The early planners of Chicago protected the lakefront. However, architects of the first high-rise buildings and early zoning regulations did not yet have a strong awareness of site improvements with positive environmental impact, such as setbacks and green or porous areas.	Large public areas were widespread in the mid-century era, bringing more sunshine into the city. Still, they were frequently composed of hard surfaces such as granite paving, which badly affected stormwater management and the urban heat island effect.	With increased zoning requirements for landscape, buildings after 1975 tend to be surrounded by more trees and have a site design sensitive to pedestrians. New city ordinances raised awareness of stormwater management.	New environmental awareness has encouraged the use of permeable surfaces, urban parks, and stormwater retention. When selecting a site, the rehabilitation of brownfield areas and pollution cleanup are encouraged. High development density and mixed-use buildings in urban areas allow better access to cleaner public and bike transportation than cars. The importance of public parks remains high, enhanced by the development of Millennium Park in recent years.
Building representation	Carson, Pirie, Scott & Company Building Marshall Field and Company Building The Pittsfield Building The Fisher Building Monadnock Building The Marquette Building	860-880 N. Lake Shore Drive 875 N. Michigan Avenue Lake Point Tower Condominium 330 N. Wabash Avenue Marina City Richard J. Daley Center Inland Steel Building Willis Tower Federal Center McCormick Place Lakeside Center S. R. Crown Hall Keck-Gottschalk-Keck apartments	Franklin Center Two Prudential Plaza 311 South Wacker Drive 900 North Michigan Water Tower Place Chase Tower Three First National Plaza	St. Regis Chicago, formerly Wanda Vista Tower One Chicago East Tower NEMA Chicago Aqua One Bennett Park Salesforce Tower Chicago 110 North Wacker
Renewable energy	–	–	After the energy crisis, ideas about integrating solar energy into buildings were being developed. However, due to long payback periods, building-integrated renewable energy was not generally used in the Central Loop.	Buildings are beginning to integrate energy generation elements such as solar panels and wind turbines. Tax incentives are making these elements more financially viable.

SUCCESSFUL RETROFITTING EXAMPLES IN CHICAGO

Retrofitting efforts in Chicago City have demonstrated a satisfactory success rate. Choosen examples from different periods showcase the implementation of retrofitting strategies. Notable instances include the Field Building, Chase Tower and Willis Tower.

Field Building

The Field Building (Fig. 1) was constructed in 1934 as a 535-feet (163.1 m) 45-story skyscraper on the site bounded by South Clark Street, South LaSalle Street and West Adams Street. The architect was the firm of Graham, Anderson, Probst & White. It is considered the last major office building erected in Chicago before the Great Depression and the World War II construction hiatus, which ended with the building of One Prudential Plaza in 1955.

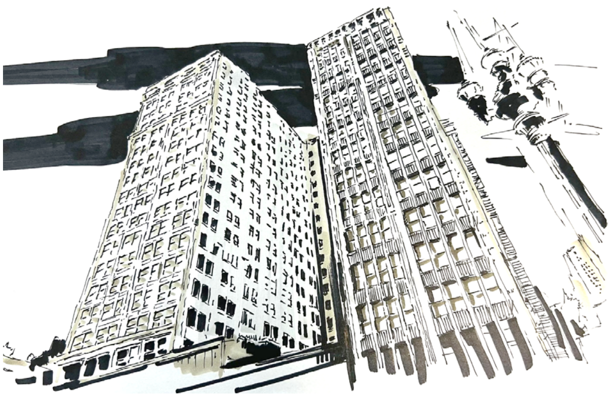

Fig. 1. Field Building

Source: © Peter Niemczak.

Many of the latest innovations, such as high-speed lifts and air conditioning, were incorporated into the building's design. The lobby features a multi-level arcade between LaSalle and Clark Streets, allowing pedestrians to walk between the two streets and access the retail space without exiting the building. The lift indicator panel and mailbox in the lobby are in an integrated design that resembles the building's exterior shape. The building rises from a four-story base that covers the entire site. The exterior of the first story is faced with polished black granite. Windows are framed with polished aluminium or Monel metal and have black and polished aluminium spandrel panels. The entrances on the east and west façades rise the entire height of the base and are also framed in black granite. Five pilasters, clad in white Yule marble, divide the bays featuring revolving doors that serve as entrances to the lobby. The upper levels are covered in limestone, with vertically grouped windows set back to accentuate the building's height. The 45-story rectangular tower is positioned at the centre of the base and is reinforced by shorter 22-story towers at each of its four corners.

Environmental Systems Design, Inc. (ESD) worked on a retrofit of the 1.2 million square feet, 44-story Bank of America building (1934) in Chicago. Improvements included updates to standby and emergency life-safety generation systems. The installation included the required generator and related life safety systems to comply with the 2000 Chicago Electric Code.

The ESD also provided lower tower electrical distribution engineering upgrades, emergency generator design, and other HVAC, plumbing, energy and lift studies and improvements.

The ESD provided LEED commissioning services and detailed retro-commissioning and re-engineering.

The commissioning process produced over $300,000 in annual savings in low-cost, immediate energy conservation measures.

The process also identified long-term energy conservation measures to be implemented as space renovations occur, anticipated to result in additional energy savings of $900,000 per year.

Chase Tower

Chase Tower (Fig. 2), located in the Chicago Loop area of Chicago, in the US. state of Illinois at 10 South Dearborn Street, is a 60-story skyscraper completed in 1969. At 850 feet (259 m) tall, it is the 14th-tallest building in Chicago, the tallest building inside the Chicago 'L' Loop elevated tracks and, as of May 2022, the 66th-tallest in the United States. JPMorgan Chase has its US and Canada commercial and retail banking headquarters here. The building is also the headquarters of Exelon. The building and its plaza (Exelon Plaza) occupy the block bounded by Clark, Dearborn, Madison and Monroe streets.

Fig. 2. Chase Tower

Source: © Peter Niemczak.

The ESD was tasked with creating a plan to revamp and enhance the mechanical, electrical, plumbing, life safety, security and control systems in the 2.4 million square feet Chase Tower. The main aim was to make the renovated building top-notch for the next 50 years by adding new and improved amenities for both the public and tenants, all while cutting down on energy use.

Willis Tower

The Willis Tower (originally the Sears Tower) is a 110-story (Fig. 3), 1,451-feet (442.3 m) skyscraper in the Loop community of Chicago in Illinois, United States. Designed by architect Bruce Graham and engineer Fazlur Rahman Khan of Skidmore, Owings & Merrill (SOM), it opened in 1973 as the world's tallest building – a title it held for nearly 25 years. It is the third-tallest building in the Western Hemisphere and the 23rd-tallest worldwide. Each year, more than 1.7 million people visit the Skydeck observation deck (the highest in the United States), making it one of Chicago's most popular tourist destinations. The building occupies a site bounded by Franklin Street, Jackson Boulevard, Wacker Drive, and Adams Street. Graham and Khan designed the building as nine square "tubes" clustered in a 3 × 3 matrix; seven tubes were set back on the upper floors. The tower has 108 stories as counted by standard methods, though the building's owners count the main roof as 109 and the mechanical penthouse roof as 110. The façade is made of anodised aluminium and black glass. The base of the building contains a retail complex known as the Catalog. The tower's lower half was initially occupied by retail company Sears, which had its headquarters until 1994, while the upper stories were rented out.

Fig. 3. Willis Tower (Formerly the Sears Tower)

Source: © Peter Niemczak.

The structure was called the Sears Tower from its construction until the naming rights were included in a 2009 lease with the Willis Group. Local area residents still refer to the building by its old name. As of April 2018, the building's largest tenant is

United Airlines, occupying around 20 floors. Other major tenants include the building's namesake, Willis Towers Watson, and law firms Schiff Hardin and Seyfarth Shaw. Morgan Stanley became the building's fourth-largest tenant in 2017.

WHY EXISTING BUILDING DO NOT RETROFIT?

Lack of a reliable system for benchmarking and comparing

Buildings use voluntary systems like Energy Star to compare themselves to other structures. Even though Energy Star is still evolving as a tool for unusual occupancy applications, it works best for commercial buildings. It does not discuss how existing structures stack up against current regulations or other structures. As a result, there is minimal rivalry or attention to energy improvement or savings.

Lenient requirements for existing buildings' energy codes

There is currently no minimum performance criterion for existing buildings, despite energy codes and ASHRAE standards becoming more demanding for new construction. Only significant renovations, and only to a limited extent, are necessary to comply. Requiring older buildings to comply with the new code could pose a significant financial challenge. However, a more practical approach could involve gradually adopting less stringent energy requirements and offering incentives during renovations to enhance the performance of existing structures. Furthermore, there is an emerging trend for publicly funded projects to incorporate mandated energy criteria.

Payback periods

Energy service companies (ESCOs) and ComEd//DCEO incentives can be used to finance projects with short payback periods (usually fewer than 10 years). In comparison, some of these incentives have even faster payback requirements of three to seven years. Longer payback initiatives are frequently avoided due to financial constraints.

Inability to sub-meter

Individual tenant lighting in business buildings is frequently not metered, and implementing such metering has a significant upfront cost. Additionally, switching from 277 to 480-volt power is frequently necessary.

Cost transfer to tenants results in a lack of motivation

Large commercial and residential structures frequently use leases or assessments to transfer base building costs onto tenants. Consequently, there is currently minimal motivation to enhance energy efficiency. However, with building occupants becoming increasingly aware of these costs, a more competitive market may eventually favour structures with lower pass-through utility rates.

Lack of personal and professional commitment and coordination

Some structures lack the benefit of proactive or knowledgeable management and operational employees. Other times, active personnel suggest energy-saving measures but fail to coordinate them with financial attempts to secure funding.

Lack of corporate support and business community engagement

A lack of corporate support can stall energy-saving projects and investments.

Financial challenges

Some building owners do not have the resources or credit scores to qualify for the loans required to fund significant energy renovations.

Considerable energy savings projects are frequently too intrusive or large-scale to be paid for as a scheduled capital investment; they are better carried out as part of a more extensive rehabilitation project. However, financing these kinds of projects may prove challenging if credit is not readily available or owners cannot raise the funds necessary to repay sizable debts annually.

System of comparison and benchmarking that is consistent

Establish a rule requiring existing structures to benchmark their energy consumption intensity.

This approach will aid in pinpointing structures with the greatest potential for energy savings. It will also encourage owners and occupants of underperforming buildings to acknowledge and disclose their energy usage.

CONCLUSIONS

It is crucial to encourage all buildings to save using existing incentives. However, the energy savings required to meet the targets outlined by the Chicago Climate Action Plan and the 2030 Challenge are too drastic to rely solely on current incentives and building owners' efforts to upgrade. To accomplish these aims, more motivational and leadership strategies will be needed. As a result, the following crucial step is to start a pattern of upgrading buildings downtown based on the 30% savings target by creating groups of buildings to cooperate as pilot projects. Based on the most significant square footage, owners and operators, a critical group of 83 buildings has been determined to construct a pilot project to have the best possible impact in the target area. If this collection of buildings (which account for over 70% of the downtown square footage) can achieve a 30–40% reduction, this will surpass the CCAP's goals. The reduction objective of 8 million mt of CO_2 for the target area stated in this chapter is consequently more aggressive than the average level of the city-wide CCAP goal, which assumes a 30% energy savings in half of all buildings. The Loop should be a leader in achieving the CCAP targets. Buildings can be grouped into energy districts based on their shared uses, locations or eras as potential options for experimental initiatives. Divining buildings into target districts might make sense to enable smaller, more targeted initiatives. Dividing buildings into target districts could be a sensible strategy to facilitate smaller, more focused initiatives. The savings potential of these pilot buildings is currently being assessed and categorised based on their current performance and the reduction techniques discussed earlier in this chapter. The pilot groups can be improved upon and linked with finance strategies particular to that group of buildings when each building is further investigated, as is covered in the Funding chapter.

It should come as no surprise that Chicago's built environment accounts for about 70% of the city's greenhouse gas emissions, given the estimated 23,000 commercial, institutional and industrial buildings dispersed throughout the city. Decarbonising this industry is, therefore, necessary to help Chicago achieve its aim of lowering GHG emissions.

The nomenclature and categorisation schemes of the International Building Code, along with green building regulations, were integrated into the city's building codes in this update. While updating building codes and initiating community projects can contribute to a reduction in greenhouse gas (GHG) emissions from buildings, achieving a complete elimination may not be feasible. The increasing prevalence of climate change combined with Chicago's growing population means that increasing building energy efficiency is becoming an increasingly important concern, especially in terms of existing commercial buildings. Not only is retrofitting buildings – essential for reducing the city's overall carbon emissions, but it also updates and renovates the existing building stock, allowing many older structures to continue to be profitable for many years. Older buildings will be able to draw new tenants and residents seeking more healthy, comfortable and efficient space once they are upgraded to modern green standards. Auditing, retrofitting and commissioning are the three processes that must be taken to boost the energy efficiency of existing buildings.

Authors' contributions

Conceptualisation: P.N.; methodology: P.N. and A.S..; validation: P.N.; investigation: P.N.; resources: P.N.; data curation: P.N.; writing – original draft preparation: P.N..; writing – review and editing: P.N. and A.S.; figures: P.N.; supervision: A.S.; project administration: A.S.

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

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DLACZEGO BUDYNKI W CHICAGO NIE SĄ MODERNIZOWANE?

STRESZCZENIE

Budynki i biura na obszarze Chicago należy dostosować do standardów efektywności energetycznej odpowiednich dla XXI wieku, zarówno ze względu na oszczędzanie środków finansowych, jak i redukcję emisji gazów cieplarnianych, która negatywnie wpływa na klimat. W niniejszym badaniu dokonano analizy koncepcji modernizacji o charakterze energooszczędnym, uwzględniając jej główne etapy oraz działania interwencyjne. Zmniejszenie zużycia energii w budynkach przekłada się na wydłużenie ich trwałości oraz redukcję długofalowego wpływu na środowisko naturalne. Stanowi to kluczowy cel modernizacji pod kątem oszczędności energetycznej. Co więcej analiza potencjalnych kierunków przyszłych badań wykazała, że istnieje konieczność przeprowadzenia dokładnej oceny i zbadania potencjału oszczędności energetycznych, związanych z różnymi wariantami i kombinacjami modernizacji. Równie istotnym aspektem będzie przeprowadzenie dokładnej oceny ekonomicznej i środowiskowej integracji tych technologii z obszarami budowlanymi. Obszar Chicago może podjąć się znaczącego zadania polegającego na uczynieniu swojej infrastruktury bardziej efektywną energetycznie dzięki wdrożeniu strategicznej integracji dostępnych zasobów i zastosowaniu istniejącej wiedzy, co przyczyni się do korzyści zarówno ekonomicznych, jak i ekologicznych dla ośmiu milionów mieszkańców tego regionu.

Słowa kluczowe: dekarbonizacja, emisja dwutlenku węgla, strategie klimatyczne, modernizacja, Chicago

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SUSTAINABLE LIVING ENVIRONMENT IN THE CONTEXT OF SOCIAL NEEDS

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ABSTRACT

A sustainable living environment should be shaped in an ecological, economical and pro-social way. The aim of this work is to draw attention to this last, often overlooked aspect in the context of designing sustainable residential architecture, what can be achieved by taking care to maintain social relations at the appropriate level. The article reviewed the existing theories of sociologists, psychologists and architects on the features of architecture and residential spaces. The analysis of literature sources showed that there are architectural elements that can support the formation of social contacts. On their basis, a set of ten evaluation criteria was developed, which can be used for further research, e.g. in the context of evaluating pro-social solutions in selected architectural and urban projects.

Keywords: sustainable environment, residential architecture, social contacts

INTRODUCTION

To obtain a fully sustainable living environment, it is not enough just to design buildings in an ecological and economical way. It is also important to meet the physical and mental needs of human beings by properly setting their relationship with the natural environment, as well as taking care to maintain social contacts at an appropriate level. Understanding the mechanisms of control of the interaction between people, buildings and the space between them can help in obtaining information on how to shape the housing environment to make it pro-social. Of course, even well-designed architecture of a residential building and the shape of the space around it cannot guarantee social contacts at an appropriate level. There are many factors influencing it. The relationship between the environment and what is felt by a human being is so complex that the ability to predict a specific dimension of this relationship seems to be impossible. However, a properly shaped living space may, to a greater or lesser extent, support the formation of social contacts between neighbours. It is about some kind of 'activity generators' that enliven residential spaces and architecture, making them more susceptible to the formation of this type of relationship.

FEATURES OF ARCHITECTURE SUPPORTING SOCIAL CONTACTS

The aim of the article is to make an in-depth analysis of the literature on architectural elements which can support the creation of social contacts from various points of view – presented not only by architects and urban planners (Christopher Alexander, Jan Gehl, Jan M. Chmielewski, Sławomir Gzell, Bartosz Czarnecki, Henry Sanoff, Kathryn McCamant, Charles Durrett) but also by ethnologists (Edward T. Hall), sociologists (Alexander Wallis, Stanisław Osowski, Waldemar Siemiński) and psychologists

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(David Canter, Augustyn Bańka, Maria Lewicka) – to obtain a broader perspective of the examined issue

As a result of the analysis of literature sources, a similarity of ideas was noticed regarding architectural solutions which may have an impact on the formation of social contacts. The quoted opinions of individual authors have been compared and compiled according to these perceived, convergent architectural solutions such as: the optimal size of the housing estate and the residential building unit; residential buildings corresponding to human scale; smooth transition between private, social and public space; common outdoor space; greenery available; common indoor spaces, service infrastructure complementing residential spaces, diversity of households; territorial distinctiveness of the neighbourhood; architectural detail.

The optimal size of the housing estate and the residential building unit

Czarnecki and Siemiński, referring to the concept of the 'behavioural swamp' created by the ethologist John B. Calhoun, formulate the idea that overcrowding causes a permanent situation of inability to maintain personal distance, i.e. to maintain a balance between being in a group and being alone. According to the authors, the development of the situation depends not only on the density index itself, but also on the cultural circle from which the members of the community come from and on the detailed lifestyle and spatial conditions (Czarnecki & Siemiński, 2004, p. 21). According to Czarnecki and Siemiński, the size of the community allowing to maintain social contacts and close neighbourly relations is between a dozen and 20–25 families. In such a community, it is possible to flawlessly recognise strangers based on full knowledge of all residents and the circle of their most frequent guests. A group of no more than 25 people is also able to maintain relations of cooperation, common goals and informal sanctions in the event of breaking established rules what allow community members to feel co-responsible for the neighbourhood space (Czarnecki & Siemiński, 2004, p. 171). The authors recommend that when designing low-rise housing estates, the scale of neighbourhood spaces should be considered, which would allow for grouping residents into communities of such a large number. However, the authors note that the possibility of integrating a neighbourhood group also depends on the type of development, population density and the way the space functions.

According to Alexander et al., the optimal group size should be between eight and twelve households (Alexander, Ishikawa, Silverstein, Fiksdahl-King & Angel, 1977/2008, pp. 202–204). According to the authors, small groups are more conducive to a sense of community. With the increase in the number of inhabitants, the identity of the group weakens, and the commitment and responsibility decreases.

McCamant and Durrett define the optimal group size between 15 and 30 households. According to the authors, such a group is small enough to be able to remember the faces of all inhabitants of the community, but also large enough to avoid those with whom it does not want to have contacts (McCamant & Durrett, 2003/1988, p. 158).

According to Chmielewski, many sociological studies confirm that the number of families living in a separate housing estate unit determines the nature of neighbourly relations. In a group of up to 20 families, social contacts are formed, between 20 and 150 families these contacts are neighbourly, while over 150 families they turn into formal contact (Chmielewski, 2010, p. 92). The author suggests that the given numbers of families should be deliberately referred to the design of units organising architectural and urban space, starting from the shaping of apartments and ending with a housing estate. In this way, they create a hierarchical set of places corresponding to an ever-increasing social community (Chmielewski, 2010, p. 94).

Gzell, in his reflections on the elements of architecture supporting the formation of social contacts, also draws the conclusion that the impact of architectural solutions which connect people in small groups helps integration processes (Gzell, 1987, p. 149).

Sociologists Wallis and Siemiński also come to the same conclusion. According to them, there are a certain number of neighbours whose faces we can recognise in our residential environment. "If the number of neighbours we meet when entering and leaving the house is too large, we adopt a defensive attitude and try not to enter into closer contact with them, even superficial contacts [own transl.]" (Wallis & Siemiński, 1974, p. 29). Wallis and Siemiński note that social control is very important in the living environment, the most common form of which is visual control. It occurs when several people appear in the same space. However, its functioning is completely different among people who associate each other's faces and among a group of people who do not know the faces of their neighbours, sometimes even completely, even though they live close to each other (Wallis & Siemiński, 1974, p. 29). Using the example of high-rise blocks of flats in the Warsaw housing estate Za Żelazną Bramą, the authors show how messages are conveyed differently in a large block of flats and in a small house. There are usually information boards on the ground floors of high-rise buildings, the content of which resembles newspaper advertisements, e.g. 'a bargain sofa for sale' (Wallis & Siemiński, 1974, p. 29). The authors note that these are anonymous messages and that in smaller residential buildings such matters are dealt with through neighbourly conversation. According to Wallis and Siemiński, the reason for this state of affairs is, among other things, too many apartments in the building, what has a huge impact on the social life of the residents (Wallis & Siemiński, 1974, p. 29).

Residential buildings corresponding to human scale

An optimal size of a residential building unit is connected with another factor influencing the formation of social contacts, which is the height of the building. It is the case because the number of apartments usually increases with the number of floors. As Wallis and Siemiński note, residents of three-, four-, eight- and 15-storey houses have different connections, acquaintances and a sense of responsibility for their environment (Wallis & Siemiński, 1974, p. 29), but not only that. The relation towards the landscape of the estate is also different when viewing it from the fourth floor and completely different from the high floors. From the windows located on low floors one can see the estate, and from those located on high ones – mainly the city (Wallis & Siemiński, 1974, p. 29). According to Kazimierz Z. Sowa, quoted by the authors: "Tall buildings distance residents from the estate, both visually and socially [own transl.]" (Wallis & Siemiński, 1974, p. 29). It is also related to a different form of communication between the floors of low-rise and high-rise buildings. An elevator is required to connect storeys in a 15-storey block, but the four-storey distance can also be covered on foot using stairs. These two different solutions also determine different types of contacts and different forms of isolation (Wallis & Siemiński, 1974, p. 29). By using the lift, we bypass all floors except our own and the ground floor, and by using the staircase, we can increase the chance of meeting a neighbour.

The influence of building height on the intensity of social relations is also noticed by Gehl. He believes that the number of contacts between neighbours significantly decreases in tall buildings. Short and spontaneous behaviours disappear to a large extent, especially in people whose apartments are located on high floors, because it is too absorbing for them to go downstairs and go outside (Gehl, 1971/2013, p. 184). The author also notes that the spaces around tall buildings take on an impersonal character. There may be benches and walking paths, but rarely something more. Users do not decorate the outdoor space with their own furniture, equipment or toys because it is too much problem for them to carry all these things out and in every time. In the face of such architectural conditions, outdoor activities become very limited, both in quantity and character (Gehl, 1971/2013, p. 184). The possibility of spontaneous reactions does not have a chance to develop here. On the contrary, in low buildings, with easier access to the external space, events inside and around the building have a 'different flow' (Gehl, 1971/2013, p. 185). Residents living in low-rise buildings do not have to make many decisions and preparations to go outside. When we notice something interesting through the window, it is easier to go outside and ask the neighbour what is going on. Such small, spontaneous contacts between neighbours can also lead to the development of deeper relationships (Gehl, 1971/2013, p. 185).

Modern urban psychologists explain that living in high-rise building can hinder a children's psychological growth. They suggest that one of the best ways for children (ages between two and seven) to become independent is to gradually allow them to go out on their own to experience the neighbourhood. However, such approach is only possible in a low-rise environment where the parents can hear and see their children from their flats' windows (Story & Saul, 2015).

Lewicka has similar observations regarding the influence of building height and social contacts. She states that numerous studies in the field of environmental psychology show that large buildings promote anonymity and create a feeling of crowding (Lewicka, 2012, p. 209). The author notes that, paradoxically, despite the large number of neighbours, the contacts between them in high-rise buildings are fewer and the bonds are weaker (Lewicka, 2012, p. 209). According to Lewicka, the most interesting theory linking the height of the building with the social behaviour of the inhabitants, and indirectly also with their emotional connection and with the place, is the theory of the architect and urban planner Oscar Newman. The researcher presented several guidelines on how to transform a 'defenceless space' (Lewicka, 2012, p. 209) into that which will defend itself. He postulated that an important premise is the existence of a relationship between the size of the building and the degree of control over the living space (Lewicka, 2012, p. 209). He assumed that security in the place of residence is best guaranteed by the residents themselves, assuming, however, that they have a sense of control over the area of their estate. According to Newman, this feeling depends on the scale and height of the building. It means that the level of control over the space of residence is the highest in the case of single-family houses, and the lowest in the case of blocks of flats (Lewicka, 2012, p. 209). Newman's theses were also confirmed by Lewicka's researches. It is worth mentioning one of them, carried out in two districts of Warsaw (Bródno and Włochy), where two types of neighbouring block buildings were compared: lower blocks of flats – up to four floors, and the so-called skyscrapers – over four floors. Residents were asked to rate their level of attachment to their place of residence. Even though both types of blocks of flats belonged to the same housing estates and were therefore administered by the same cooperative, the inhabitants of lower buildings declared a stronger attachment to the place of residence and had closer neighbourly relations, and felt safer and a bit more willing to get involved in the benefit of their estate than residents of neighbouring skyscrapers (2012, p. 214).

These studies show a significant difference in the impact on building social relationships between low-rise and high-rise buildings. In this case, the boundary was the fourth floor, beyond which different statements regarding the intensity of neighbourly contacts were observed. The four-storey limit as a pattern for building residential blocks was also defined by Alexander. According to the author, the connection between the apartment and the street disappears above the third floor: "visual details lose focus, people talk about what is happening downstairs as if it were some game from which they are completely excluded [own transl.]" (Alexander et al., 1977/2008, p. 118). It looks completely different if a person observes the world from behind a window located on the first or second floor. He then notices "people, their faces, leaves, shops [own transl.]" (Alexander et al., 1977/2008, p. 118). According to Alexander, respecting the four-storey limit is also an appropriate way to maintain the proper relationship between building height and people's health (Alexander et al., 1977/2008, p. 118).

Smooth transition between private, social and public space

Considerations on the impact of building height on the intensity of social contacts showed how important it is to be able to easily move between the private space of apartments and the social space organised around residential buildings. Chmielewski, writing about the social character of space, notes that the concept of 'community' is being broaden quite freely in Poland today (Chmielewski, 2010, p. 84). The difference between the public good and the social good is blurring (Chmielewski, 2010, p. 84).

Chmielewski reminds us how important it is to properly zoning a space and smooth transitions between private, social and public spaces. According to the author, a social space can be called a set of places in which the goals and interests of the inhabitants are most fully expressed and implemented since the community is created by a group of people united by some common goals or interests (Chmielewski, 2010, p. 84). These are primarily nodal points around residence, as well as areas where the same people meet multiple times (Chmielewski, 2010, p. 85). Public space should be combined with everything that is state and municipal, i.e. space organised in accordance with the regulations of state and local law, completely subject to the control of local authorities and managed by these authorities and maintained in proper condition. This space should be common and publicly available to all who wish to stay there (Chmielewski, 2010, p. 85). It is therefore important to connect residential buildings or housing estates located in the suburbs with the city centre if the location of a given building or housing estate does not provide it with sufficient contact with public space.

Gehl provides valuable tips how to design the boundary between the private zone of apartments and the social space. According to the author, the building plan must be designed so that the events taking place inside the house can freely flow outside (Gehl, 1971/2013, p. 187). The entrance should be designed in the way which will best enable to pass through, both functionally and psychologically. Intermediate corridors, additional doors, and especially changes in the level difference between indoors and outdoors should be avoided so that events can freely flow outwards and inwards (Gehl, 1971/2013, p. 187).

According to architect and planner Dorit Fromm, establishing contacts is facilitated using soft boundaries between what is private and what is common, as well as between what is common and what is public. It creates a greater opportunity for visual and verbal contact. An example of the use of such soft boundaries is a kitchen facing neighbourhood spaces. It is important that the worktop in the kitchen should be located under the window so that a person, while cooking, can see what is happening outside (Fromm, 1991, pp. 12–14).

Hall, observing people in various social systems, distinguished four types of distances occurring between people. These are: intimate, individual, social and public distance. For each of them, the author distinguishes a closer and a further phase (Hall, 1976, p. 186). Hall points out that the factor determining which distance people perceive from each other depends on a given system: on the bonds between the contacting individuals, as well as on what they feel towards each other (Hall, 1976, p. 186). Each of these distances corresponds to appropriate distances between people, i.e. the intimate distance is up to 45 cm, the individual distance is between 45 m and 1.2 m, the social distance is from 1.2 m to 3.6 m and the public distance is over 3.6 m (Hall, 1976, p. 186). These distances correspond to specific distances in space. Therefore, according to Hall, learning about these different contact zones and the specific emotions, bonds and activities associated with each of them is extremely important also when designing space. “However, if we look at a human being as someone stuck in a network of invisible spatial envelopes with measurable quantities, architecture will appear to us in a completely different light [own transl.]” (Hall, 1976, p. 186).

Common outdoor space

The above research indicates another important aspect that influences the development of social contacts. It is the presence of a common outdoor space centred around the building complex.

According to Wallis, one of the basic human needs is the expression of one’s personality by individuals and social groups (Wallis, 1971, p. 74). Social needs, however, require appropriately designed common spaces to be fulfilled. Therefore, it is necessary to design open, semi-open and closed, semi-private and public spaces, and shape the space so that it provide various social situations and the needs of contacts with various requirements (Wallis, 1971, p. 74).

According to Alexander, common area is a place for meetings and smooth joint activities undertaken by the residents of a given group of houses. This function is not fulfilled by larger spaces of common land served by entire housing estates, such as public squares and parks. They are necessary for the functioning of the entire neighbourhood, but they do not ensure the implementation of functions common to the inhabitants of a group of households (Alexander et al., 1977/2008, p. 344). According to Alexander, common space should constitute at least 25% of the area within each group of houses, adjoining or close to the houses (Alexander et al., 1977/2008, p. 523). This area should also be well sunny, preferably open to the south (Alexander et al., 2008, p. 523), and provide various common functions, such as: a vegetable garden, a playground, an area for local sports, etc. (Alexander et al. 1977/2008, p. 346).

Gehl also draws attention to the quality of the designed common spaces. According to the author, if the outdoor space is of poor quality, only necessary behaviours take place there (Gehl, 1971/2013, p. 11). However, if the space is of high quality, the necessary behaviours occur with approximately the same frequency, but their duration increases significantly because the physical conditions are better. Optional activities also occur in high-quality spaces as the place and situation prompts people to stop, sit, eat and play. Well-designed spaces between buildings, where people can meet and then stay in a given place for a while longer, can also turn into more advanced forms of social contacts (Gehl, 1971/2013, p. 11).

Greenery available

As a result of the analysis of various literature sources, it was noticed that several authors see the potential in building social relationships in various types of green spaces, such as: home gardens, nearby parks, as well as by making common spaces more attractive in a form of trees or shrubs planted along the main paths located around the building.

Gehl believes that neighbourly relations between buildings can develop if opportunities are offered to stay outside in the semi-private gardens located in the transition zone between the buildings and the street (Gehl, 1971/2013, p. 11). In an Australian study cited by Gehl, covering 17 terraced streets, it turned out that front gardens played a very important role in the activity in street spaces and that stationary outdoor activities and conversations between neighbours had particularly good conditions as a direct consequence of the existence of semi-private outdoor spaces in a form of gardens in front of buildings (Gehl, 1971/2013, p. 189). These studies also showed that gardening activities often took much more time than necessary. If neighbours showed up, work was eagerly interrupted in favour of a short chat over the fence (Gehl, 1971/2013, p. 191). In this way, the accessible garden fulfilled a double function: in addition to being purely utilitarian, it also contributed to the creation of social contacts.

Gzell, writing about a garden from a semiotic perspective, defines it as a sign emphasising the privacy of the area, which is ‘a dam and a lock’ (Gzell, 1987, p. 148) separating the private space of an apartment or house from the space used socially.

Alexander pays attention to maintaining the appropriate distance between green areas and buildings: “People need green areas for walks. If these areas are close to home, they will use them. However, if the green area is more than three minutes’ walk away, then the need to walk will be dominated by the distance which must be covered [own transl.]” (Alexander et al., 1977/2008, p. 310). The research conducted by Alexander shows that it is very important for people to be able to regenerate strength while walking (Alexander et al., 1977/2008, p. 310). Such a walk among greenery creates an opportunity for passive contacts, i.e. contacts when we only see or hear other people. However, just meeting someone can also be the seed for other, more complex forms of social behaviour (Gehl, 1971/2013, p. 191).

Common indoor spaces

The observations of McCamant and Durrett (1988/2003, pp. 184–187) as well as Alexander (1977/2008, p. 628) show that common areas located in the centre of a residential building support the creation of social contacts. The shape and location of these common areas is very important. According to Alexander, the passageway used by all residents every day should run tangentially to and open to common spaces (Alexander et al., 1977/2008, p. 628). This kind of location of the common space is the best possible because, on the one hand, thanks to its tangential location to the main passage, it does not disturb people passing by, and on the other hand, thanks to its openness, it encourages people to stop and see what is happening inside (Alexander et al., 1977/2008, p. 628). Centrally located common spaces serve to maintain contacts between residents. In addition to meeting rooms or internal halls, such common spaces may also include: laundry rooms, kitchens, drying rooms, carpentry rooms, and even pantries or bicycle rooms. Performing various activities together helps to establish neighbourly relationships.

Gehl, citing research conducted in rural communities, calls shared laundry rooms and wells "overriding catalysts for informal contacts [own transl.]" (Gehl, 1971/2013, p. 117). In San Vittorino Romano, where the research was carried out, leaving a bucket by the well turned out to be an intentional act. It was left so that one can come back for it at any time if someone showed up to talk to (Gehl, 1971/2013, p. 117).

It should be noted that all the rooms mentioned above, such as laundry rooms and kitchens, should have a complementary function. It is important that residents also have private kitchens in their apartments or houses, what gives them independence and the ability to decide whether they want to spend time only with their immediate family or join a group of other people living in a residential building or in a complex of residential buildings. However, it should be admitted that the lack of such a choice, as in the case of, for example, a communal laundry room, may result in more effective creation of social contacts.

Service infrastructure complementing residential spaces

Buildings for other purposes also play an important role in the spatial structure of the estate, such as: shops, schools, services, universities, which attract people during the day (Alexander et al., 1977/2008, p. 263).

Czarnecki and Siemiński, citing Gerda R. Wekerle and Carolyn Whitzman's research, confirm that an appropriate variety of functions is conducive to urban life, social control and interpersonal contacts during the day and in the evening (Czarnecki & Siemiński, 2004, p. 112). According to the authors, it can be obtained using services, including first-need services (2004, p. 112). It is also important that the introduced services are associated with local employment, which is particularly conducive to social control. Employees of such services, who are also members of the neighbourhood community, pay more attention to what is happening in the space surrounding the services than employees commuting from other parts of the city (Czarnecki & Siemiński, 2004, p. 112). As Czarnecki and Siemiński note, this is a return to the traditional 'corner shop', which is consistent with the principles of sustainable development set out in Agenda 21 (Czarnecki & Siemiński, 2004, p. 112). This also reduces commuting to work and strengthens the neighbourhood community (Czarnecki & Siemiński, 2004, p. 112).

Gzell, comparing streets in districts distant from Warsaw with the Śródmieście Passage (in the central district of Warsaw), states that this latter, thanks to the huge number of services, is popular among city residents, which ensures its vitality. On the contrary, streets located outside the city, made up exclusively of residential buildings, despite unusual urban solutions, are not socially accepted. They lack a nameless crowd of passers-by stimulating unusual behaviour (Gzell, 1987, p. 140).

Gehl notes that the requirements which must be met in public spaces include the needs of contact, knowledge and stimulation. They belong to the group of psychological needs (Gehl, 1971/2013, p. 115). Satisfying them is often connected with basic physical needs, such as eating, drinking or sleeping. As the author states, adults rarely go to the city with the expressed intention of satisfying the need for contact, however, as research shows, adults working at home spend three times as much time for shopping than those who work outside the home (Gehl, 1971/2013, p. 115). These conclusions lead to the assumption that many daily shopping trips are not only caused by replenishing missing resources, but also result from the desire to meet psychological needs (Gehl, 1971/2013, p. 117). Other types of development located among residential buildings create additional opportunities for social contacts between neighbours. The usual shopping trip described above also becomes an excuse to contact other people. Thanks to this, physical and psychological needs are met at the same time.

Diversity of households

Another important criterion in the light of considerations on social housing architecture is the diversity of households. Today's housing patterns are increasingly separating different types of households from each other. In some areas large apartments are designed, in others bedsits. In this way, we obtain living spaces where only elderly people live, only young families with children or only single people. The result is a situation where people do not have the opportunity to experience the full human life cycle.

According to Alexander: "At no point in the life cycle a person is self-sufficient. People need support and validation from those who have already reached a higher stage in the life cycle. At the same time, they need support from those who are at the same stage of the life cycle as they are. [own transl.]" (Alexander et al., 1977/2008, p. 193). According to the author, contact with people of different ages is possible only when the balance of life cycles corresponds to the types of housing available in the neighbourhood (Alexander et al., 1977/2008, p. 193). Therefore, in the process of designing residential architecture, it is important to pay attention to the possibility of creating various types of apartments, tailored to the needs of people of different ages.

Gehl also has a similar point of view. He also argues that children's demands on the external environment should be considered simultaneously with those of other age groups. According to the author, "Supporting outdoor activities of adults and older people is in itself considered as the best possible way to support children's activities and the environment in which they grow up [own transl.]" (Gehl, 1971/2013, p. 131).

While diversity in terms of age is confirmed in the works of many authors, the mixing of representatives of different professions, and therefore people with different financial status, is not so obvious. Wallis, analysing the socialist housing policy formulated in the 1950s in Poland, which consisted in the maximum mixing of various professional groups in the place of their residence, i.e. both in houses and housing estates, states that there are indications that this policy failed (Wallis, 1971, p. 67). According to Wallis, neither excessive economic, cultural and prestigious dissimilarities between neighbours, nor another extreme in a form of excessive homogeneity of the estate's inhabitants, lead to the maximisation of necessary contacts (Wallis, 1971, p. 67–68). The ideal seems to be a compromise between these two different possibilities. According to Wallis, the most appropriate situation seems to be when people can choose their own place of residence (Wallis, 1971, p. 68).

A research described by Lewicka shows that living in an ethnically mixed neighbourhood increases mutual tolerance, but at the same time reduces trust in neighbours and attachment to the community, which in turn causes a decrease in motivation to undertake various forms of social activity for the sake of the place of residence (Lewicka, 2012, p. 189). However, the factor having the greatest impact on social cohesion turned out to be the average income of a neighbourhood unit (Lewicka, 2012, p. 190).

Territorial distinctiveness of the neighbourhood

According to Wallis, the identification of residents with the housing estate as a socio-spatial integrity is an important but usually underrated factor of integration in a housing estate. "The architectural separation and fencing off an estate (sometimes only symbolically) strengthen the sense of social distinctiveness of its inhabitants and allow them to create a sense of responsibility for it, even though it remains available to every passer-by" (Wallis, 1971, p. 76). This feeling is manifested in the way residents take care of the space, where they feel they belong, e.g. tending lawns, keeping it clean, etc. (Wallis, 1971, p. 67).

Gzell has a similar opinion, claiming that the creation of integration processes of small groups of people requires the adoption of appropriate spatial solutions (Gzell, 1987, p. 149). The author, citing research conducted by the Greater London Council (GLC), indicates that in addition to using the lowest possible buildings and introducing space distinguishing features, a factor integrating residents is also the complete surrounding of the courtyard with buildings. The GLC study lists two types of interiors: closed, approximately equal in length and width, and linear – a short street (1987, p. 149).

Czarnecki and Siemiński also claim that private streets, internal courtyards and closed building complexes serve to improve the territoriality of residents and collective responsibility for the place and for others (Czarnecki & Siemiński, 2004, p. 20). The authors, citing Irwin Altman's research, indicate the empirical manifestations of the phenomenon of territoriality in human behaviour as: "occupying or using places or objects, as well as demarcating and defending the zone of home space [own transl.]" (Czarnecki & Siemiński, 2004, p. 19).

Alexander claims that a gate is also an architectural element that strengthens the territoriality of a given area. It marks the end of one type of activity or place and the beginning of another (1977/2008, p. 282). "Gates can take many forms: a gate in the literal sense, a bridge, a passage between buildings standing close to each other, an avenue of trees, a passage leading through a building. They all fulfil the same functions: they mark the point of crossing the border and help to distinguish it [own transl.]" (Alexander et al., 1977/2008, p. 282).

Architectural detail

Gehl notes that it is not enough to just create a good space and let people move around in it. There must also be appropriate conditions for moving and staying in spaces, as well as for participating in a wide range of social and recreational activities (Gehl, 1971/2013, p. 129). The quality of individual elements of the environment plays a key role here. The details of these spaces, with the smallest component parts, are the determining factors. The space must be attractive for walking, standing, sitting, looking, listening and talking. Such an important detail may be, for example, a bench located by the entrance door, protected from rain and wind, with a good view of the street. A seemingly modest piece of furniture can become quite an important way of maintaining life between buildings. The author emphasises that benches should be placed so that they define a semi-private domain in front of the house. A low wall, plants and a tree can help to create this domain (Gehl, 1971/2013, p. 129).

Gzell points out that details in architecture and urban planning should not only be perceived from a functional, aesthetic or compositional way, but also from a semiotic one. According to the author, details such as a row of benches in a park carry certain meanings and shape the resident's awareness and the atmosphere of the environment (Gzell, 1987, p. 147). According to Gzell, signs emphasising the privacy of the area include all details separating the apartment or house from the public space, i.e.: a fence, a wall, a hedge, a change in level, terrain modelling and any vertical barrier separating the private area, equipped with a closed passage that emphasises the existence of an intimate, 'own' world behind the fence (Gzell, 1987, p. 148).

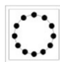
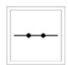
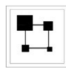
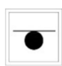
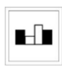
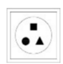
A similar point of view related to the detail in architecture and urban planning is presented by Wallis. He claims that: "Each element of small architecture, apart from the basic function for which it was designed, performs secondary functions which are a derivative of its size, shape, material, place in the landscape, and in some cases – e.g. a newsstand – also a derivative of its specific information values" (Wallis, 1971, p. 126). A small architecture, in a form of benches, walls, fountains or a newsstand, also supports various social phenomena occurring between residents and related to the perception, feeling and use of various types of space. According to Wallis, its most important task is to structure the space and introduce its own, intimate scale. According to the author, the small architecture also designates places for social contacts (Wallis, 1971, p. 127). The already mentioned bench and newsstand define these places not only because of the function assigned to them in advance, but also because they make it easier for human memory to capture images of the surroundings. They constitute a set of visual reference points in space, and as we spend more time with them, they also become an element of our identification with this space (Wallis, 1971, p. 128–129).

A detail in architecture does not have to mean only small architecture, but also the quality of a given space, thanks to elements such as properly selected lighting or properly designed surface. Czarnecki and Siemiński point out the importance of proper illumination of space. According to the authors, the space after twilight often has a completely different structure than during the daytime (Czarnecki & Siemiński, 2004, p. 116). The same place may have good visibility during the day, be safe and frequently visited, and at night turns into a space completely devoid of visibility, abandoned and dangerous. If, for example, an important space for residents, which is a place of intense social contacts during the day, is not sufficiently illuminated at night, it is highly probable that after twilight, when all services increasing urban traffic are closed, this space would lose its importance in favour of another better lit space (Czarnecki & Siemiński, 2004, p. 116).

RESEARCH RESULTS

The aim of the article was to make an in-depth analysis of the literature on architectural elements which can support the creation of social contacts from various points of view – presented not only by architects and urban planners but also ethnologists, sociologists and psychologists. As a result of the analysis of literature sources, a similarity of ideas was noticed regarding architectural solutions which may influence the formation of social contacts. The cited opinions of individual authors were compared and collected (Table 1) according to the identified, convergent architectural solutions in a form of 10 evaluation criteria such as: the optimal size of the housing estate and the residential building unit; residential buildings corresponding to human scale; smooth transition between private, social and public space; common outdoor space; greenery available; common indoor spaces; service infrastructure complementing residential spaces; diversity of households; territorial distinctiveness of the neighbourhood; architectural detail.

Table 1. Architectural elements supporting the formation of social contacts

No	Evaluation criterion	Description	Pictogram
1	The optimal size of the housing estate and the residential building unit	maximum number of apartments in one building: 30 maximum number of apartments in the development quarter: 150	
2	Residential buildings corresponding to human scale	maximum number of floors in a residential building: 4	
3	Smooth transition between private, social and public space	The boundary between private and social space is designed in such a way that events happening at home can flow freely outside. The boundary between social and public space separated by a system of buildings, a wall or a hedge. Social space well connected to the city centre.	
4	Common outdoor space	A common outdoor space is of high quality, well-sunlit and designed in such a way that each resident has easy access to it.	
5	Greenery available	Home gardens, green areas, parks, trees and shrubs making common spaces more attractive.	
6	Common indoor spaces	Common internal spaces located tangentially to the passages most frequently used by residents. Rooms for spending free time together or rooms where residents can perform everyday activities together, such as: kitchens, laundry rooms.	
7	Service infrastructure complementing residential spaces	Services located on the ground floor of a residential building or in the quarter to which the analysed building belongs.	
8	Diversity of households	Age diversity of residents. A diverse layout of building plans adapted to the requirements of residents of different ages.	
9	Territorial distinctiveness of the neighbourhood	Closed development layout with a courtyard in the middle, short, private street. Architectural elements strengthening the territoriality of a given area, e.g. a gate.	
10	Architectural detail	Small architecture which structures external spaces and becomes an element of residents' identification with this space. Quality of space: properly selected lighting, properly designed surface.	

Source: own research.

The optimal size of the housing estate and the residential building unit

Opinions of both sociologists and architects specify the maximum number of families in one residential building between 20 and 30. It was decided to adopt the widest possible range of the numerical limits given by the authors. Thus, the optimal number of families, and therefore also apartments in one residential building, was set as 30. Citing Chmielewski's research, the maximum number of apartments in the entire building block was also assumed to be 150.

Residential buildings corresponding to human scale

Based on research conducted by psychologist Lewicka, as well as the arguments presented by Alexander, the maximum height of the building was assumed to be four storeys.

Smooth transition between private, social and public space

All of the above-mentioned literature sources confirm the importance of proper zoning of space and smooth transition between private, social and public space. It was assumed, in accordance with Gehl's instructions, that the boundary between private and social space should be designed in such a way that events happening at home can flow freely outside. However, the boundary between social and public space should be clearly separated, e.g. by the arrangement of buildings, a low wall or a hedge. However, social space should not be radically separated from public space. It is also important to connect further buildings with the city centre if the location of a given building or housing estate does not provide it with sufficient contact with public space.

Common outdoor space

Both the analysis of architectural designs and theoretical research have shown that the common external space organised around the building complex is an element supporting the creation of social contacts. What is important, it is not only the existence of a common space, but also its location, enabling an easy access to it for each resident; the space is of high quality, well sunlit and shaped to serve for various social situations and the needs of contacts of various kinds.

Greenery available

Based on the conclusions of Gehl, Gzell and Alexander, resulting from observations of residential buildings and adjacent spaces, it was assumed that available greenery, in a form of home gardens, nearby parks, as well as making common spaces more attractive in a form of trees or shrubs, can be helpful in building social relationships.

Common indoor spaces

Research by both architects and environmental psychologists has shown that common spaces located inside the building maintain social contacts. It has been also adopted after Alexander that common, internal spaces should be located tangentially to the passages used by all residents on a daily basis to facilitate spontaneous contacts.

Service infrastructure complementing residential spaces

The analysis of literature sources has shown that an appropriate variety of functions is conducive to urban life, social control and interpersonal contacts. It is therefore important that there be services in the residential building (e.g. on the ground floor), as well as in its immediate surroundings (e.g. in the quarter where the building under study is located), especially the basic ones, such as a grocery store, pharmacy.

Diversity of households

For the purposes of this assessment criterion, it was decided to consider only the diversity of households in terms of age. It was decided to omit ethnic, cultural and professional diversity due to the fact that Wallis's opinion seems to be correct: neither excessively economic, cultural and prestigious distances between neighbours, nor excessive homogeneity of the estate's inhabitants lead to the maximisation of the necessary.

Territorial distinctiveness of the neighbourhood

Theoretical research presented by Gzell, Wallis, Czarnecki and Siemiński showed that the urban forms most conducive to the creation of social contacts are a closed building system with a courtyard in the middle and a short, private street. It will also be important the presence of architectural elements strengthening the territoriality of a given area, which, according to Alexander, is for example a gate.

Architectural detail

Many authors point out that urban detail in a form of small architecture is important in maintaining social relations, as it not only structures external spaces, but also, with the length of contact with it, becomes an element of our identification with this space. The presence of architectural details expressed in the quality of a given space, i.e. properly selected lighting or properly designed surface, is also important.

DISCUSSION

Ten evaluation criteria presented above can be used for further research, e.g. in the context of evaluation of pro-social solutions in selected architectural and urban projects, not only Polish examples but also European ones, because they are based on universal human needs, Architectural elements supporting the formation of social contacts, developed for this work, set general conditions of social architecture without limiting the creativity of its creators. The similar evaluation criteria were used by the author of these article to evaluate Polish and European projects using participatory design (Kosk, 2016, pp. 1471–1474; Kosk, 2017, pp. 35–37), but they can also be used in the evaluation of any other residential project to find individualities in their applications and to assess methods by which the considered assessment criteria were achieved.

It should also be noted that architecture can support the creation of social contacts not only when all the evaluation criteria developed here are met. Such an eventuality may only indicate the maximum possibility of social contacts occurring in the analysed case study.

This is also confirmed by the research carried out by the author of this work (Kołacz & Podlasek, 2024, pp. 1–19) in three flat blocks being a part of a bigger urban block in Austria. In the study area, although all three analysed architectural buildings forming part of the mentioned urban block did not meet the assessment criterion regarding building height (seven floors instead of four), a lot of social contacts between neighbours were observed since many other assessment criteria considered here were met in these projects. One of the buildings was designed in such a way that its shape consists of a series of gradually rising sections. As the cor of this project pointed out, the building cannot be considered as seven storeys high, but is instead composed of different combinations of heights. This arrangement, reminiscent of a residential hilltop, may lead to more social interaction between neighbours than in a traditional seven-storey building. While looking out of a seventh-floor window makes it difficult to initiate a conversation with, for example, someone in the courtyard, the terraced layout of the building allows to establish relationships with a neighbour living on a terrace on a lower floor (Kołacz & Podlasek, 2024, p. 11).

As noted by Al-Kodmany, tall buildings are becoming increasingly an integral response to massive urbanisation. However, this building typology has unique challenges and issues, and therefore, planners, architects, community leaders, politicians, and the public at large bear the responsibility of finding effective ways to integrate them in cities in a sustainable manner (Al-Kodmany, 2018, p. 25). The researcher lists many threats that are associated with the tall buildings not only in social but also economical and ecological aspects. However, Kodmany's studies do not conclude that all tall building developments are unsustainable. It depends largely based on place, culture, climate, location, and quality of design and construction. In some countries, such as Singapore, given by the author as an example, excellent design coupled with cultural practices has resulted in socially successful high-rise developments (Al-Kodmany, 2018, p. 26).

CONCLUSIONS

In the introduction of the work, attention was drawn to the importance of meeting the physical and mental needs of man by appropriately setting his relationship with the natural environment, as well as maintaining social contacts at an appropriate level. The research conducted here, analysing the available literature sources, was aimed at presenting the mechanisms that control the interaction of people, buildings and the spaces between them. As a result, ten evaluation criteria were developed, which are practical recommendations for architects and urban planners on how they should shape the housing environment to make it pro-social.

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STRESZCZENIE

Zrównoważone środowisko zamieszkania powinno być kształtowane w sposób ekologiczny, ekonomiczny i prospołeczny. Celem pracy jest zwrócenie uwagi na ten ostatni, często pomijany, aspekt w kontekście projektowania zrównoważonej architektury mieszkaniowej, który możemy osiągnąć poprzez dbanie o utrzymanie relacji społecznych na odpowiednim poziomie. W artykule dokonano przeglądu istniejących teorii socjologów, psychologów i architektów na temat cech architektury i przestrzeni mieszkalnych. Analiza źródeł literaturowych wykazała, że istnieją elementy architektoniczne, które mogą wspierać kształtowanie kontaktów społecznych. Na ich podstawie opracowano zestaw dziesięciu kryteriów ewaluacyjnych, które mogą posłużyć do dalszych badań, np. w kontekście oceny prospołecznych rozwiązań w wybranych projektach architektoniczno-urbanistycznych.

Słowa kluczowe: zrównoważone środowisko, architektura mieszkaniowa, kontakty społeczne

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MACHINE LEARNING IN CIVIL ENGINEERING ON THE EXAMPLE OF PREDICTION OF THE COEFFICIENT OF PERMEABILITY

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ABSTRACT

This paper investigates the application of the machine learning techniques in the civil engineering, focusing on the prediction of permeability coefficient. Permeability coefficient is an important parameter in various civil engineering projects including groundwater flow analysis, soil stabilisation and geotechnical engineering. Traditional methods for estimating permeability are time-consuming and often based on laboratory tests. The machine learning offers a promising approach to predict it more efficiently and accurately. This paper studies several machine-learning techniques, verifying their applicability to predict the permeability coefficient for sands. The article analysed the predictive performance of the artificial neural network (ANN), the random forest (RF), the gradient boosting (GB) and the linear regression (LR). The most accurate algorithm in this case turned out to be the gradient boosting for which the coefficient of determination was 0.995, the mean absolute error was less than 0.001 and the root mean square error was 0.001.

Keywords: machine learning, coefficient of permeability, prediction

INTRODUCTION

In the discipline of civil engineering, the integration of the machine learning has proven to be an increasingly widely developed and tested technique for improving various aspects of project planning and execution. The prediction of permeability coefficient, an important parameter in assessing fluid flow through natural and anthropogenic soils, is an example of the application of the machine learning techniques. Traditionally, an estimation of the permeability coefficient requires time- and resource-consuming laboratory tests. Machine learning offers an approach based on data from previous observations, which after looking for correlations in the data of features describing the phenomenon, allows to increase the accuracy of its estimation (Naranjo-Pérez, Infantes, Fernando Jiménez-Alonso & Sáez, 2020; Pardalos, Panos, Rassia & Tsokas, 2022). The search for new solutions to optimise investment costs is particularly important, given the changing economic situation in the construction market, which has been caused by COVID-19 and the war in Ukraine (Szymanek, 2022).

Machine learning algorithms such as regression models, decision trees and neural networks can be trained on historical data covering various soil properties and permeability values. Through a process of learning from these data, these algorithms notice relationships and patterns that are often not apparent in conventional analysis methods. The predictive power of these models lies in their ability to generalise from the data they have learned. This allows them to predict new data with a high degree of accuracy in estimating the permeability coefficient for different soil types.

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The machine learning models can uncover non-linear correlations and relationships that may be overlooked by traditional methods. This holistic understanding of complex interactions enables engineers to make more informed decisions when designing civil engineering projects where the permeability coefficient is a key consideration. Using the machine learning to predict the permeability coefficient not only exemplifies the symbiosis of technology and civil engineering but also highlights the potential for transformative advances in the broader field. As data collection and computational capabilities continue to evolve, it is foreseeable that such applications will continue to redefine traditional practices, enabling more efficient, accurate and innovative approaches to civil engineering projects (Reich, 1997; Melhem & Nagaraja, 2007; Kosinov, Trach & Trach, 2023).

Additionally, the incorporation of the machine learning to predict not only permeability coefficient, but also other geotechnical parameters is causing a paradigm shift in how civil engineers approach complex challenges. By adopting data-driven methodologies, engineers are empowered to make evidence-based decisions using insights derived from massive data sets accumulated over time. One remarkable advantage is the ability of the machine learning models to adapt to changing scenarios. As new data become available, models can be tuned and updated, ensuring that predictions remain relevant and accurate. This dynamic aspect of the machine learning fits perfectly with the dynamic nature of civil engineering projects, where conditions and variables are subject to change.

Moreover, the integration of the machine learning does not replace traditional engineering knowledge, but complements and extends it. The ability to interpret these models allows engineers to gain deeper insights into the factors affecting permeability. As the field of civil engineering evolves, the machine learning has the potential to be applied to more innovations. By automating some aspects of data analysis and prediction, engineers can devote more time to critical thinking, problem solving and creativity. This allows a shift in focus to pave the way for breakthroughs that were previously hampered by time-consuming tasks (Reich, 1997; Naranjo-Pérez et al., 2020).

This paper presents an estimation of the coefficient of permeability using various machine learning techniques, starting from the traditional predictive linear regression method and contrasting it with several more modern and developed machine learning techniques – the artificial neural network, the random forest and the gradient boosting. As a result, it verified the view that these techniques allow for more efficient estimation of the filter coefficient, with increasingly newer algorithms providing opportunities to reduce estimation errors.

MATERIAL AND METHODS

The analysis was carried out for sands with the grain sizes presented in Figure 1. The grain sizes were within the range shown in the figure. The study of the coefficient of permeability was performed using the constant head method. In addition, material properties were considered, such as volumetric density ranging from 0.99 g·cm^{-3} to 1.83 g·cm^{-3}, porosity 0.29 to 0.61 [−], index porosity 0.40 to 1.56 [−], grain size curvature index from 1.07 to 1.16 [−] and homogeneity index from 1.94 to 2.40 [−].

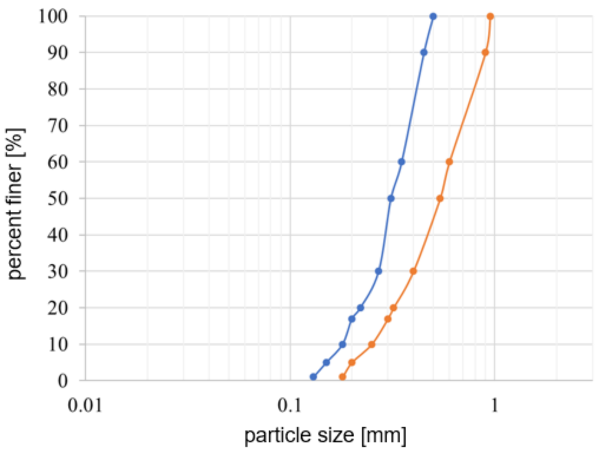

Fig. 1. Range grain size curves for the materials analysed

Source: own work.

One of the first and widely known predictive techniques is the least squares method – linear regression. It is still finding applications for the verification of simple feature relationships. Throughout the 1990s

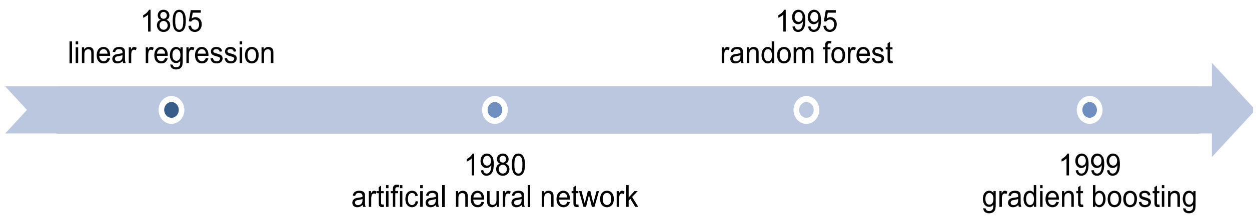

Fig. 2. Diagram of the formation of the machine learning techniques

Source: own work.

and the last two decades (Fig. 2), the development of the algorithm has significantly accelerated and can be said to be directly proportional to the development of computer techniques and capabilities. Several predictive techniques were used in the analysis, which are characterised further.

The linear regression

The linear regression is a statistical method employed to model the association between a dependent variable, also referred to as the target, and one or more independent variables, known as predictors or features. The principal objective of the linear regression is to determine the optimal linear equation that accurately characterises this relationship (Barbur, Montgomery & Peck, 1994; Weisberg, 2005; Seber & Lee, 2012). This equation takes the form:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_n x_n + \square, \qquad (1)$$

where:

y – dependent variable (target),

$x_1, x_2, \ldots, x_n$ – the independent variables (features),

$\beta_0, \beta_1, \ldots, \beta_n$ – the coefficients representing the impact of each feature on the target,

$\square$ – the error term representing the difference between the predicted and actual values.

The primary aim of the linear regression is to estimate the coefficients ($\beta_0, \beta_1, \ldots, \beta_n$) which minimise the sum of squared differences between predicted and actual values of the dependent variable. This optimisation process is often accomplished through techniques like the least squares method. Linear regression operates under the assumption of a linear relationship between the features and the target. It finds applications across diverse domains, including prediction, correlation analysis and assessment of variable influence. Variants such as multiple linear regression (with multiple predictors) and polynomial regression (addressing certain nonlinear relationships) extend their adaptability (Hu et al., 2019; Maulud and Abdulazeez, 2020).

The artificial neural network

The artificial neural network (ANN) is a machine learning model inspired by the architecture of the human brain. It comprises interconnected nodes, referred to as neurons, arranged in layers: input, hidden (one or more) and output. Neurons are connected through weighted connections. The artificial neural networks undertake various tasks, encompassing regression, classification and pattern recognition. The process involves:

– Input layer: neurons represent data features.
– Hidden layers: neurons process inputs through mathematical operations, often involving weighted sums and activation functions. Hidden layers enable the network to capture intricate data relationships.
– Activation functions: neurons employ activation functions to introduce nonlinearity. Common functions include sigmoid, ReLU and tanh.
– Output layer: The final hidden layer connects to the output layer, generating predictions. The number of output neurons varies based on the task (e.g. regression, classification).
– Training: ANNs learn by adjusting connection weights to minimise a loss function. Back propagation computes gradients of loss concerning weights, guiding weight updates through optimisation techniques such as gradient descent.

The objective is to identify weights that minimise loss, involving iterative weight updates to reduce loss. Techniques like stochastic gradient descent are commonly employed.

The artificial neural networks are adept at modelling both linear and nonlinear relationships, providing flexibility for complex tasks. The deep neural networks (DNN), equipped with multiple hidden layers, excel in capturing intricate patterns. Designing and training ANNs necessitate careful consideration of architecture, hyperparameters and data to prevent issues like overfitting (Suzuki & Soleimanian Gharehchopogh, 2012; Lagaros, 2023).

The random forest

The random forest is the machine learning ensemble method used for both classification and regression tasks. It is based on the concept of decision trees and combines multiple individual decision trees to create a more robust and accurate predictive model. The random forest starts from creating multiple decision trees. To introduce diversity among these trees, each tree is trained on a randomly sampled subset of the training data, with replacement. This technique is known as bagging. In addition to sampling data, the random forest introduces randomness in feature selection. When creating each split in a decision tree, the algorithm considers only a random subset of the available features. This prevents individual trees from becoming overly specialised and reduces the risk of overfitting. The individual decision trees created using bagging and feature randomness combine to form the random forest ensemble. For regression tasks, the final prediction is often the average of predictions from all trees. For classification tasks, the ensemble's prediction can be determined by a majority vote among the individual trees. To predict a new data point, the input is passed through each individual tree in the random forest and the final prediction is aggregated according to the ensemble method – average for regression or majority vote for classification (Breiman, 2001; Cutler, Cutler & Stevens, 2012; Louppe, 2014).

The gradient boosting

The gradient boosting is an ensemble method utilised for regression and classification tasks. It assembles a potent model by amalgamating predictions from weak learners (often decision trees) in a sequential manner. The process commences with a rudimentary prediction (e.g. mean of target). It computes residuals, indicating the disparity between actual target values and initial predictions, then constructs trees sequentially to predict negative gradients of the loss function and introduces a learning rate parameter to scale tree predictions before their addition to the ensemble. A smaller learning rate fosters gradual and stable learning. New trees' predictions enhance the existing ensemble's performance. The boosting process continues until a predefined number of trees is attained or a specific performance threshold is reached.

The gradient boosting excels in capturing intricate relationships within (Friedman, 2002; Velthoen, Dombry, Cai & Engelke, 2021).

These algorithms are foundational tools within the realm of the machine learning, each offering distinct strengths and applications. A schematic of the estimation process using the machine learning algorithms is shown in Figure 3. Ten-fold cross-validation, a resampling technique for evaluating the machine learning models on limited data, was used to validate the model. The data (n = 261) was collected, cleaned and divided into 70% training samples and 30% test samples. Cross-validation helps estimate the model's predictive ability on unseen data. The k-fold parameter divides the data into groups, used to evaluate

Fig. 3. Diagram of the estimation process using the machine learning algorithms

Source: own work.

model performance. This method provides a less biased estimate of model capability (Browne, 2000).

The final model's reliability was confirmed through average skill scores and measures of variance. Error analysis was employed to evaluate individual model performance. The evaluation included the artificial neural network, the random forest and the gradient boosting algorithms; linear regression was used as a reference and control algorithm. The results were verified by error analysis and the following values were estimated for each model:

– coefficient of determination (R^2):

$$R^2 = \frac{\Sigma_{i=1}^{N}(\hat{y}_i - \overline{y})^2}{\Sigma_{i=1}^{N}(y_i - \overline{y})^2}, \qquad (2)$$

– mean absolute error (*MAE*):

$$MAE = \frac{\Sigma_{i=1}^{n}\left|y_i - \hat{y}_i\right|}{n}, \qquad (3)$$

– root mean square error (*RMSE*):

$$RMSE = \sqrt{\frac{1}{N}\Sigma_{i=1}^{N}(y_i - \hat{y})^2}. \qquad (4)$$

RESULTS AND DISCUSSION

The estimation results for the learning and test samples are presented in Figure 4. Coefficient of determination, *MAE* and *RMSE* were calculated for each of the algorithms and each of the trials according to Eqs (2)–(4). Figure 4 presents plots of the accuracy of the fit of the estimation results to the data obtained from the trials. The lowest values of fit, R^2 were obtained for the linear regression algorithms and were equal to 0.833 for the learning sample and 0.800 for the test sample, the *MAE* was 0.003, the *RMSE* was 0.004; for the neural network, R^2 was 0.833 for the learning sample and 0.801 for test sample, the *MAE* was 0.003, and the *RMSE* was 0.004. The best results were obtained for the gradient boosting algorithm for both samples: R^2 was 0.995, the *MAE* was less than 0.001 and the *RMSE* was 0.001.

The reasons for differences in estimation accuracy should be sought in the characteristics of individual algorithms. Among other things, the type of task for which the algorithm is constructed may be of significance in the case of linear regression which is mainly used in regression tasks. In the case of the ANN algorithm, its application is comprehensive, because it can be used for regression and classification tasks. The same is true for the random forest and the gradient boosting. Another issue is handling: dealing with nonlinearity in the case of linear regression is limited to modelling linear relationships. The ANN perfectly captures both linear and nonlinear dependencies. The random forest and the gradient boosting effectively handle nonlinear relationships.

It is also important that the structure of the model linear regression is characterised by a simple structure involving a linear equation. ANN has a complex architecture with interconnected layers of nodes. Random forest forms a set of decision trees and the gradient boosting is a set of sequentially improved models. The architecture of the model affects its interpretability. The linear regression allows high interpretability due to the linear equation. The ANN is less interpretable due to its complex structure. Random forest offers insight into the meaning of the function. Gradient boosting is less interpretable compared to linear models. Performance and complexity are also not negligible, especially for complex estimation tasks. Linear regression is simple and computationally efficient; in the case of ANN the algorithm is designed for complex and computationally intensive issues. Random forest and gradient boosting are sustainable performances for solving complex problems, but these techniques can be computationally demanding. An important issue from the point of view of evaluating the correctness of the estimation is the control of overfitting. Linear regression is a technique prone to overfitting with complex relationships. The ANN is prone to overfitting, especially with small data sets. Random forest is immune to overfitting due to the nature and construction of the algorithm. Gradient boosting can cause overfitting but is less likely compared to single decision trees.

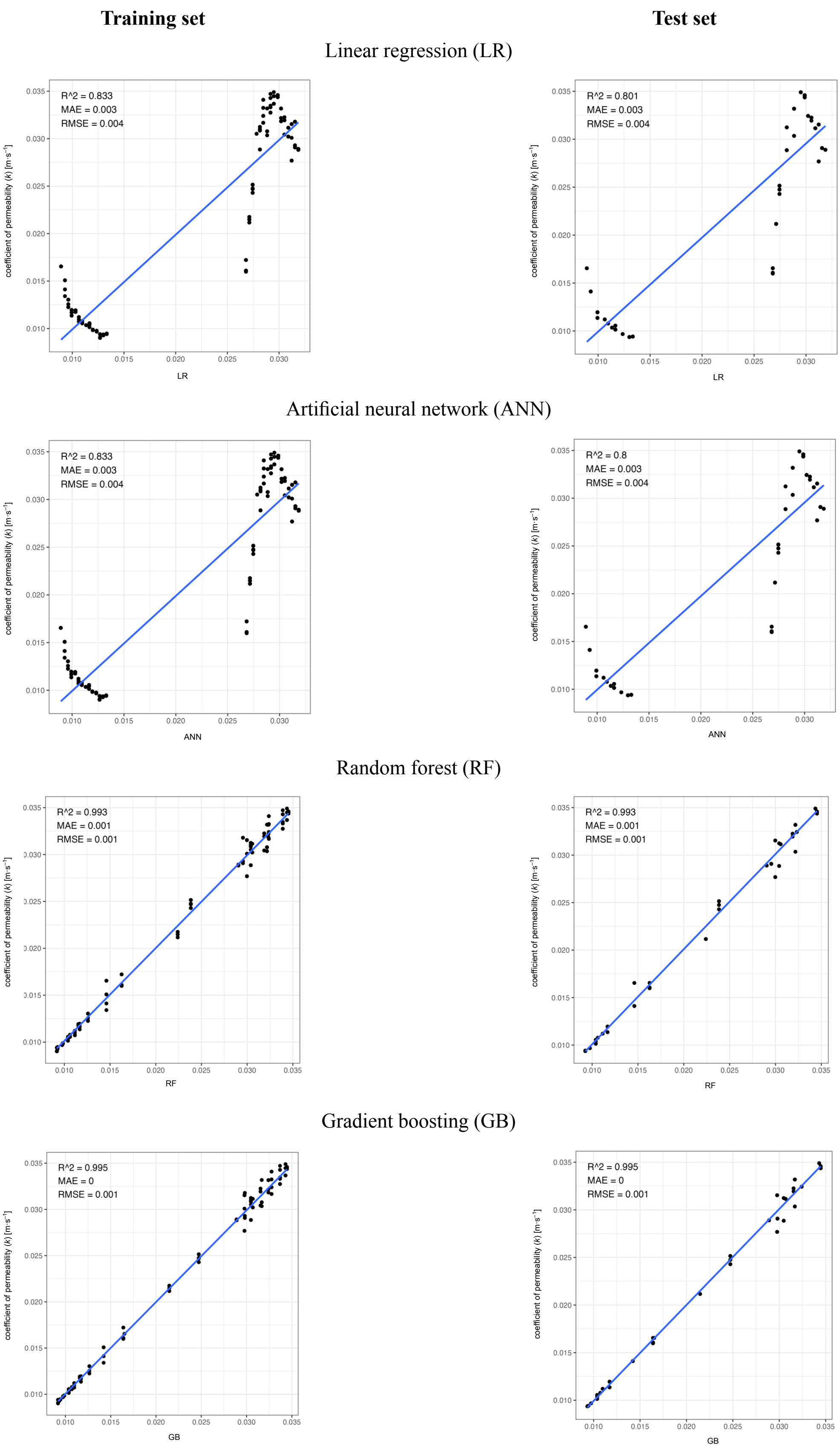

Fig. 4. Estimation results for the training and test set

Source: own work.

CONCLUSIONS

The machine learning techniques offer significant potential for predicting the permeability coefficient in civil engineering. By leveraging large datasets and complex algorithms, these methods provide more efficient and accurate predictions compared to available empirical formulas. The permeability coefficient prediction plays a crucial role in groundwater flow analysis, soil stabilisation and geotechnical engineering applications. However, further research and validation are necessary to ensure the reliability and applicability of the machine learning models in real-world civil engineering projects. The algorithms analysed in the article vary in capability, complexity and suitability for different types of data and tasks. The choice depends on factors such as data characteristics, interpretation requirements, performance expectations and available computing resources. In the case of the analysed soil – sands, the algorithm with the highest predictive efficiency turned out to be the gradent boosting whose matching of the prediction results with the data derived from laboratory tests amounted to 0.995. At the same time, it should be noted that to generalise, the data obtained should be analysed on a wider database and based on a larger number of materials.

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UCZENIE MASZYNOWE W INŻYNIERII LĄDOWEJ NA PRZYKŁADZIE PRZEWIDYWANIA WSPÓŁCZYNNIKA PRZEPUSZCZALNOŚCI

STRESZCZENIE

W niniejszym opracowaniu zbadano zastosowanie technik uczenia maszynowego w inżynierii lądowej, koncentrując się na przewidywaniu współczynnika przepuszczalności. Współczynnik przepuszczalności jest istotnym parametrem w różnych projektach inżynierii lądowej, takich jak: analiza przepływu wód gruntowych, stabilizacja gruntu i inżynieria geotechniczna. Tradycyjne metody szacowania przepuszczalności są czasochłonne i często opierają się na testach laboratoryjnych. Uczenie maszynowe oferuje obiecujące podejście do jego przewidywania w sposób bardziej wydajny i dokładny. W niniejszym artykule przeanalizowano kilka technik uczenia maszynowego, weryfikując możliwość ich zastosowania do przewidywania współczynnika przepuszczalności dla piasków. W artykule przeanalizowano skuteczność predykcyjną artificial neural network (ANN), random forest (RF), gradient boosting (GB) i regresji liniowej (LR). Najdokładniejszym algorytmem w tym wypadku okazał się GB, dla którego współczynnik determinacji wyniósł 0,995, średni błąd bezwzględny był na poziomie poniżej 0,001, a błąd średniokwadratowy wyniósł 0,001.

Słowa kluczowe: uczenie maszynowe, współczynnik filtracji, predykcja

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AN APPLICATION OF GABIONS FOR DESIGN OF COASTAL PROTECTION STRUCTURES IN LAKES

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ABSTRACT

With large areas of water reservoirs and lakes, the wave runoff distance is also large, resulting in the high waves in the wind blow direction. These waves intensively disrupt the coast of the lake or water reservoir. Another intense factor of coastal erosion is ice. A lot of engineering measures for the coastal protection of reservoirs and especially for lakes are used: reinforced concrete slabs, blocks, jibs, cellular systems (geosynthetics), etc. An eroded coastline, reshaped by installing a coastal protection structure using gabion construction, is analysed in this research. Gabions are designed to protect banks and slopes from fast water flow (water speed over 5 $m \cdot s^{-1}$) and ice impacts. They are designed according to geotechnical principles, assessing stability according to the limit design situations specified in Eurocode 7 (EN 1997-1). The aim of this work is to illustrate the features of wave and ice loads and geotechnical design situations evaluated in the design of a coastal protection structure made of gabions.

Keywords: coastal protection structures, waves and ice impacts, gabions, geotechnical design situations

INTRODUCTION

The coastline shows constantly varying nature due to tidal effects and changes in wind and wave climate. Sediment movement, erosion and accretion are responsible for changing the morphology of coastal area. Human activities/interference is also responsible for changes in the coastline (Kudale, Kudale & Kulkarni, 2021).

With large areas of water reservoirs and lakes, the wave runoff distance is also large, resulting in the high waves in the wind blow direction. These waves intensively disrupt the coast of the lake or water reservoir. The wave forces are dominant and decisive in the design of coastal structures. Structural stability as well as functional performance of a coastal structure depends on design wave conditions (Kudale & Bhalerao, 2015).

An integrated coastal engineering numerical model is presented by Karambas and Samaras (2017). The model simulates a linear wave propagation, wave-induced circulation, sediment transport and bed morphology evolution. The assessment of wave energy dissipation on the three barriers was executed using two approaches – ordinary dean functions and the concept of monotonic approximate seabed proposed by Różyński (2020) and by Różyński and Cerkowniak (2022). Coastal protection structures influence on diffraction and reflection of waves simulation based on 3D wave hydrodynamics model is presented by Sukhinov, Chistyakov and Protsenko (2021).

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Another intense factor of coastal erosion is ice (Łabuz, 2015). Some researchers (Smith & Houser, 2022) think opposite – ice cover reduces erosion during the winter months by limiting fetch across the lake and creating a protective ice foot at the shoreline.

The effect of an ice cover depends on many factors: the length of the ice field, the thickness of the ice, a layer of snow, the temperature of the ice and the rates at which it is expanding and shrinking, the coefficient of friction against the material of the structure and soil, the mechanical properties of the ice and the shape of the water body and structure. An ice cover may exert the following actions against inclined structures: static pressure due to continuous thermal expansion as a result of a temperature rise in the ambient medium, the dynamic effect of floating ice blocks and a breakaway effect when the water level changes.

Coastal protection generally refers to the protection of people, infrastructure and other assets from the negative consequences resulting from flooding (high water levels and/or wave overtopping) and erosion (Möller, 2019). A lot of engineering measures for the coastal protection of reservoirs and especially for lakes are used: reinforced concrete slabs, blocks, jibs, cellular systems (geosynthetics), etc. Dikes may also be constructed from various materials, most commonly: geosynthetic tubes, geo-cells, reinforced concrete, boulders, steel, or gabions (Razali et al., 2023).

Coastal protection based on ecological engineering provides a new concept of resisting coastal zone disasters (Luan, Li, Chen, Geng & Liu, 2020).

Innovative technical solutions for the development of bioengineering systems combined with gabions are presented by Kurbanov, Sozaev, Shogenov & Karshiev (2021).

This paper focuses on coastal protection structure made from gabions. Gabions and mattresses assortment is useful as an integral part of shore fortification and protection, the river bed and slope lining structures. Modern box gabions consist of rockfill material enlaced by a basket or a mesh, shaped like a rectangular box (Chanson, 2015). Gabion type retaining structures constitute one of the most economical and efficient solutions for stabilization of natural ground slope. Gabion walls are also preferred for the efficiency of the drainage instead of gravity walls. As a construction material, the advantages are their stability, low cost, flexibility and porosity (Toprak, Sevim & Kalkan, 2016).

Gabions are extensively used for earth retaining structures as well as hydraulic structures: retaining walls, bridge abutments, wing walls, culvert headwalls, outlet aprons, shore and beach protection walls, temporary check dams (Cherkasova, 2019).

Gabions participate in the formation of ice conditions and generate icing problems. For example, an ice-stone mass with a certain porosity and strength properties, which creates favourable conditions for the floating and shifting of the gabions, separation from the basic ice mass, interaction with ice layers and attrition by the moving ice, is formed when the gabions are frozen into ice. Structures formed by gabions should be able to resist against different types of ice loads. The artificial measures to increase ice thickness and thin gabion mattress in the context of climate warming were explained by Chunjiang et al. [s.a.].

The assessment of the technical conditions of bank protection in Poznań on hydrotechnical structures are presented by Hämmerling, Walczak, Walczak and Zawadzki (2019).

Numerical modeling of failure mechanisms in articulated concrete block mattress is presented by Safari Ghaleh, Aminoroayaie Yamini, Mousavi and Kavianpour (2021).

The aim of this work is to illustrate the features of wave and ice loads and geotechnical design situations evaluated in the design of a coastal protection structure (made from gabions) in lakes.

The following research tasks were define:
- calculation of the wave and ice loads and evaluation of design situations for design of a gabion retaining wall for shore protection;
- checking the stability of a typical gabion retaining wall in case of overturning and sliding;
- evaluation of the strength of the gabion retaining wall base according the loss of load-bearing capacity.

MATERIAL AND METHODS

The object of investigation

Construction site of the designed structure is located in the Meteliai village, Seirijai eldership, Lazdijai district municipality (Fig. 1).

The reinforced concrete retaining wall was installed for shore protection. The existing retaining wall has serious problems: as a result of a washed foundation plate base, the retaining wall has lost stability, settled unevenly and ruptured (Fig. 2).

It is suggested to demolish reinforced concrete retaining wall and replace it by newly designed

Fig. 1. The eroded coast of the lake Meteliai

Source: © Geoportal.lt.

Fig. 2. The deformations and deteriorations of existing reinforced concrete retaining wall

Source: photos by the authors.

retaining wall made of gabions. Gabion elements are preferred because of their flexibility, permeable nature, low costs, environmentally friendliness and aesthetically pleasing nature in comparison with gravity retaining walls (Toprak, Sevim & Kalkan, 2016).

Recycled materials (crushed concrete from existing wall) can be placed into the gabion cage. The use of crushed concrete (large grains) can be applied as filling of mattresses or gabions (Fiske, 2014; Kawalec, Kwiecien, Pilipenko & Rybak, 2017).

Scheme of retaining wall for shore protection

The coastal protection structure according to Lithuanian Building Technical Regulation STR 1.01.03:2017 (Classification of structures), (Lietuvos Standartizacijos Departamentas, 2017) is classified as hydraulic structures. Coastal protection structures are classified in consequence class CC2 according to Lithuanian Building Technical Regulation STR 2.02.06:2004 (Hydraulic structures. Basic provisions. Annex 1), (Lietuvos Standartizacijos Departamentas, 2004a).

The walls of gabion baskets and grid-stone mattresses with planting will be used as retaining structures for eroded shoreline and bank strengthening. The appropriate filtration materials have to be chosen for gabions so that they protect from washing elements of soil from under the baskets. Geotextile is most commonly used for this purpose (Fig. 3). Engineering infrastructure (coastal protection structure) should be designed and installed with the least possible change in the nature of the landscape and without polluting the environment.

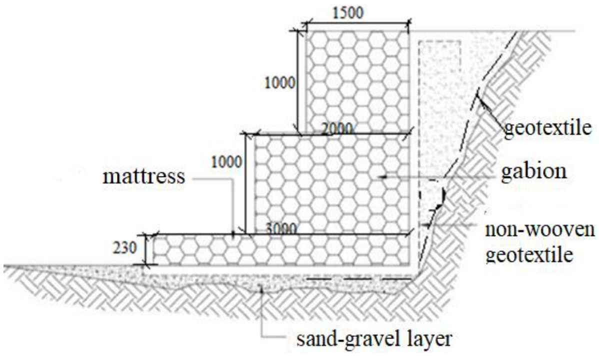

Fig. 3. Scheme of retaining wall for shore protection

Source: own work.

Methodology for calculating loads applicable to coastal protection

The consequence class of hydraulic structures is determined in accordance with Lithuanian Building Technical Regulation STR 2.02.06:2004 (Hydraulic structures. Basic provisions. Annex 1).

Loads acting on the shore protection structure are calculated in accordance with Lithuanian Building Technical Regulation STR 2.05.15:2004 (Effects and loads on hydraulic structures), (Lietuvos Standartizacijos Departamentas, 2004b).

Wave loads are calculated in accordance with Lithuanian Building Technical Regulation STR 2.05.15:2004 (Section X. Wind loads on shore protection structures and ship waves on canal slope protection. Section I. Wind loads on shore protection structures).

The maximum values of the horizontal (P_x) and vertical (P_z) representative projections of the linear loads from wind-caused waves on the vertical seawall (when the waves roll down) must be determined according to the wave lateral and back pressure graphs (Fig. 4). The value of the pressure (p_r), shown in the graphs, must be calculated as follows:

$$p_r = \rho g \, (\Delta z_r - 0.75 h_{br}), \tag{1}$$

where:
ρ – water density [kg·m^{-3}],
g – gravitational acceleration [m·s^{-2}],
Δz_r – lowering the water level from the calculated water level in front of the vertical wall, when the wave rolls down [m]; it depends on the distance between the structure and the water boundary line: $\Delta z_r = 0$ when $a_l \geq 3h_{br}$ and $\Delta z_r = 0.25h_{br}$ when $a_l < 3h_{br}$,
h_{br} – height of falling waves [m].

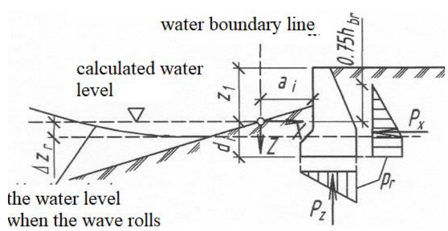

Fig. 4. Graphs of the wave pressure on the vertical seawall during the wave rolling down

Source: own work.

Ice loads were calculated in accordance with Lithuanian Building Technical Regulation STR 2.05.15:2004 (Effects and loads on hydraulic structures: Section II. Loads of moving ice fields into structures; Section III. Loads and effects on structures due to thermal expansion of continuous ice cover; Section V. Loads of ice on the structure as the water level changes).

According to the STR 2.05.15:2004, the impact force of moving ice fields in contact with section of structure with a vertical front edge of any shape is calculated in two cases (the lower value is taken for further calculations):

– when it is hit by single ice floes:

$$F_{c,w} = 0.07 v h_d \sqrt{A R_c} \text{ [MN]}, \quad (2)$$

– when ice collapses:

$$F_{b,w} = 0.5 R_c b h_d \text{ [MN]}, \quad (3)$$

where:

v – ice field movement velocity (determined on the basis of field investigations, and in their absence, as follows: for rivers and flood-exposed sea sections – keeping the flow rate constant; water reservoirs and seas – at a level equal to 0.03 wind velocity, determined during the drifting of the ice with a probability of 1%), [m·s^{-1}],

h_d – calculated ice thickness (taken as for rivers – 0.4 m at 1% probability), [m],

A – area of the ice field (determined on the basis of field investigations in the area under consideration or in the vicinity of the water body), [m^2],

R_c – standard compressive strength of ice [MPa].

When salinity is below 2‰, then the linear load resulting from a thermal expansion (q) of the ice cover should be calculated as follows

$$q = h_{max} k_l p_t, \quad (4)$$

where:

h_{max} – maximum ice cover thickness at 1% probability [m],

k_l – coefficient equal to 1 [–],

p_t – pressure of deformation of the ice expanding due to temperature changes [MPa]:

$$p_t = 0.05 + 11 \cdot 10^{-5} v_{t,a} \eta_i \mu, \quad (5)$$

where:

$v_{t,a}$ – maximum rate of air temperature rise (from 6 h of four-timed observations) [°C·h^{-1}],

η_i – coefficient of ice creep [MPa·h^{-1}], calculated according to the formulas:

when $t_i \geq -20$°C,

$$\eta_i = (3.3 - 0.28\, t_i + 0.083\, t_i^2) 10^2; \quad (6)$$

when $t_i < -20$°C,

$$\eta_i = (3.3 - 1.85\, t_i) 10^2; \quad (7)$$

t_i – ice temperature [°C], calculated as follows:

$$t_i = t_b h_{rel} + 0.5 v_{t,a} \cdot t \cdot \psi, \quad (8)$$

where:

t_b – initial air temperature from which the temperature rise begins [°C],

h_{rel} – relative thickness of the ice cover, taking into account the influence of snow:

$$h_{rel} = h_{max}/h_{red}, \quad (9)$$

where:

h_{red} – reduced thickness of the ice cover, calculated as follows:

$$h_{red} = h_{max} + 1.43 h_{s,min} + 2.3/\alpha, \quad (10)$$

where:

$h_{s,min}$ – minimum thickness of the snow cover, determined by natural observations; if there is no snow, $h_{s,min} = 0$ is taken,

α – heat transfer coefficient of air and snow cover [W·m^{-2}],

if there is snow, then $\alpha = 23\sqrt{v_{w,m} + 0.3}$, (11)

where:

$v_{w,m}$ – average wind speed [m·s^{-1}],

ψ, φ – dimensionless coefficients determined by h_{rel} and the dimensionless parameter F_0:

$$F_0 = 4 \cdot 10^3 t / h_{\text{red}}^2. \quad (12)$$

The vertical force of the ice cover frozen to the structure as the water level changes (F_d) [MN], (Fig. 5), should be calculated as follows:

$$F_d = 0.2 l v_d t_d (h_{\max}^3 / \Phi)^{0.25}, \quad (13)$$

where:
l – length of the static section at the level of ice exposure [m],
v_d – speed of rise or fall of the water level [m·h^{-1}],
t_d – time during which the deformation of the ice cover occurs when the water level changes [h],
$h_{\max}$ – maximum ice cover thickness at 1% probability [m],
Φ – dimensionless time function expressed by the formula:

$$\Phi = 1 + 300[t_d + 50(1 - e^{-0.4 t_d})] / \eta_i, \quad (14)$$

where:
η_i – coefficient of ice creep [MPa·h^{-1}].
t_d, e – see explained early.

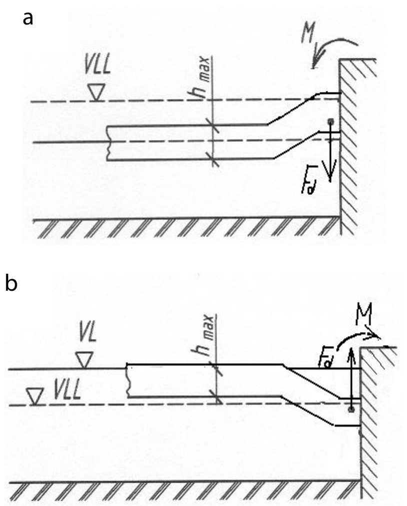

Fig. 5. Schemes of the ice cover frozen to the structure loads calculations, when the water level (VL) changes: a – when the VL is falling, b – when the VL is rising; VLL – water level when the ice is standing

Source: STR 2.05.15:2004.

The moment of force (M) [MN·m^{-1}], which is absorbed by the structure from the frozen ice cover when the water level rises or falls (Fig. 5), should be calculated according to the formula:

$$M = 2 l v_d t_d \sqrt{h_{\max}^3 / \Phi}, \quad (15)$$

where:
l, v_d, t_d, $h_{\max}$, Φ – see explained early.

Note: The limiting force moment ($M_{\lim}$) [MN·m^{-1}], cannot be greater than this calculated according to the formula:

$$M_{\lim} = 0.167 l h_{\max}^2 R_t R_c (1 + 2k_e) / (R_t + R_c), \quad (16)$$

where:
R_t, R_c – tensile and compressive strength of ice cover [MPa], calculated according to the formulas:

$$R_t = R_{t,y} \cdot e^{-400 t_{\text{cal}} / \eta}, \quad (17)$$

$$R_c = R_{c,y} \cdot e^{-400 t_{\text{cal}} / \eta}, \quad (18)$$

where:
$R_{t,y}$, $R_{c,y}$ – the average values of the ice yield strength in tension and compression [Pa],
t_{cal} – the time during which the water level changes by a size equal to the thickness of the ice [h],
k_e – coefficient assuming the following values:

$e^{-400 t_{\text{cal}} / \eta}$	0.8	0.85	≥ 0.90
k_e	1.0	1.5	2.0

$h_{\max}$, $\eta_i l$ – see explained early.

Hydrodynamic forces lead further the structural deformations and settlement to geotechnical instability. Failure due to hydrodynamic forces can be avoided by adopting proper dimensions and suitable weight for gabion box (Sherlin, Sundaravadivelu & Saha, 2018).

Methodology of geotechnical stability analysis

Gabion retaining walls should be designed as mass gravity walls, using standard soil mechanics principles. No allowance should be made for the strength or mass of the wire mesh and the density of the filled gabions should be taken as 60% of the density of the solid rock used.

According to the limit design situations specified in Eurocode 7 (European Uninon [EU], 2004) the stability should be analysed for: overturning, sliding, bearing failure, localised deformation or failure of the wall and deep seated failure of the retained slope.

Geotechnical stability is analysed numerically using software GEO5 for different loads. The calculation methods for wall analysis:

- active earth pressure calculation: Coulomb,
- passive earth pressure calculation: Caquot–Kerisel,
- earthquake analysis: Mononobe–Okabe,
- shape of earth wedge: calculate as skew,
- allowable eccentricity: 0.333,
- verification methodology: according to EN 1997,
- design approach: 2 – reduction of actions and resistances.

RESULTS AND DISCUSSION

The results of wave loads calculation

With large areas of lake the wave runoff distance is also large, resulting in the high waves in the wind blow direction (Fig. 6). The initial parameters for wave loads calculation are presented in Table 1. The results of wave loads calculation are presented in Table 2.

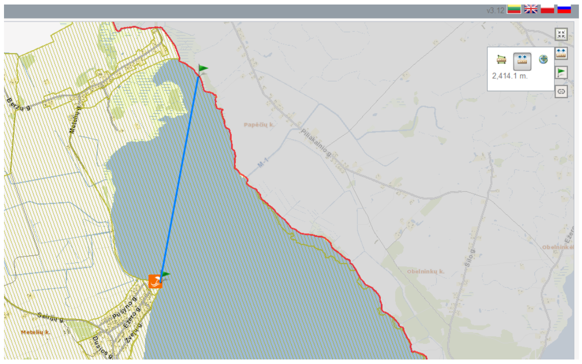

Fig. 6. The wave runoff distance

Source: © Geoportal.lt.

Table 1. Initial parameters for wave load calculation

Slope angle (acc. to Fig. 4)	0°			10°			15°		
Wind speed (V_w) [m·s^{-1}]	20	25	30	20	25	30	20	25	30
Average wave height (h) [m]	1.57	1.57	1.72	1.57	1.57	1.72	0.88	1.57	1.72
Average wave length (λ), m	40.95	41.01	44.68	40.95	41.01	44.68	41.93	41.01	44.68
Average wave period (T) [s]	7.86	7.85	8.19	7.86	7.85	8.19	7.86	7.85	8.19
Depth at first wave break (d_{cr}) [m]	1.99	2	2.18	1.99	2	2.18	2.11	2	2.18
The depth of the last wave break (d_{cru}) [m]	0.62	0.63	0.68	0.62	0.63	0.68	0.66	0.63	0.68
Calculated maximum wave height (h_j) [m]	1.57	1.57	1.72	1.57	1.57	1.72	1.67	1.57	1.72
The maximum rise of the wave crest above the calculated level (n_u) [m]	1.44	1.45	1.58	1.44	1.45	1.58	1.53	1.45	1.58

Source: own work.

Table 2. Wave load calculation results

Slope angle (acc. to Fig. 4)	0°			10°			15°		
Wind speed (V_w) [m·s^{-1}]	20	25	30	20	25	30	20	25	30
When the waves roll down, the projection of the wave is horizontal (P_x) [kN·m^{-1}]	6.08	6.13	7	6.08	6.13	7	6.72	6.13	7
Addition point of horizontal load (z_1) [m]	–0.12	–0.13	–0.16	–0.12	–0.13	–0.16	–0.15	–0.13	–0.16
When the waves recede, the projection of the wave is vertical (back pressure) (P_z) [kN·m^{-1}]	7.68	7.72	8.44	7.68	7.72	8.44	8.21	7.72	8.44

Source: own work.

Based on the results of the wave loading calculations, Table 2 shows that the changes of slope angle from 0° to 15° directly affect wave loads calculation results only at wind speed $V_w = 20\ m \cdot s^{-1}$.

The results of ice loads calculation

The initial parameters for ice loads calculation are presented in Table 3. The results of ice loads (Figs 5 and 7) calculation are presented in Table 4.

Table 3. Initial parameters for ice loads calculation

Parameter	Value
Ice temperature at the air-ice contact zone (T_u) [°C]	5
Ice temperature at the air-ice contact zone during ice movement (T_l) [°C]	4
Calculated temperature drop (dT) [°C]	5
Ice thickness (h_d) [m]	0.4
Maximum area ice field at 1% probability (A_l) [m^2]	50
Speed of ice field movement (v_l) [$m \cdot s^{-1}$]	1
The average snow cover thickness during the calculation period when the temperature drops (h_s) [m]	0.2
Average wind speed during the temperature drop (V_w) [$m \cdot s^{-1}$]	10
Change in water level (h_0) [m]	0.4

Source: own work.

For various ice thicknesses (0.3 m, 0.4 m, 0.5 m), variable wind speed (10 $m \cdot s^{-1}$, 15 $m \cdot s^{-1}$, 20 $m \cdot s^{-1}$), variable speed of ice field movement (0.5 $m \cdot s^{-1}$, 1 $m \cdot s^{-1}$, 1.5 $m \cdot s^{-1}$), change in water level (0.3, 0.4 and 0.5 m) as well as various ice field areas (50 m^2, 100 m^2, 150 m^2), the following ice loads have been calculated: 1) the impact force of moving ice fields in contact with structure [P_1 or $F_{b,w}$ – Eq. (3)]; 2) ice impact due to the temperature expansion of the continuous ice cover (P_3 or q – Eq. (4)]; 3) the vertical force [P_6 or F_d – Eq. (13)] and moment [M_1 or M – Eq. (15)] of the ice frozen on the structure, with the changing water level. The results of the calculations are presented in Table 4.

Based on the results of the ice loading calculations, Table 4 shows that the changes of ice thickness directly affect calculation results of all types of the ice loads. The changes of average wind speed during the temperature drop (V_w) have impact on values of horizontal linear loads on structures due to ice cover thermal expansion effect (P_3 or q). The changes of speed of ice field movement (v_l) from 0.5 $m \cdot s^{-1}$ to 1.5 $m \cdot s^{-1}$ and ice field maximum area (A_l) from 50 m^2 to 150 m^2 directly influences calculation results of the horizontal load of moving ice fields on a structure

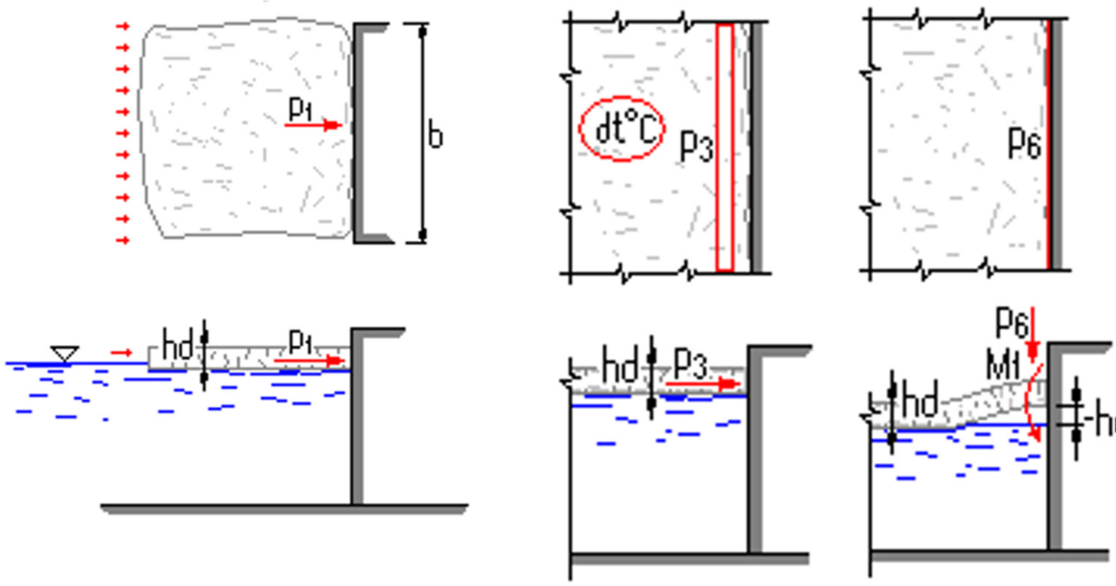

Fig. 7. The illustration of ice loads

Source: own work.

Table 4. Calculation results of ice loads

Parameter which has been changed	Horizontal load of moving ice fields on a structure with a vertical front edge (P_1 or $F_{b,w}$) [kN]	Horizontal linear load on structures due to ice cover thermal expansion effect (P_3 or q) [kN·m^{-1}]	Vertical force of the ice cover frozen to the structure as the water level changes (P_6 or F_d) [kN·m^{-1}]	Moment absorbed by the structure from the frozen ice cover when the water level rises or falls (M_1 or M) [kNm·m^{-1}]
Ice thickness (h_d) 0.3 m	131.62	34.6	4.5	19.74
Ice thickness (h_d) 0.4 m	175.49	29.2	5.58	35.1
Ice thickness (h_d) 0.5 m	219.36	41.4	6.6	54.84
Average wind speed during the temperature drop (V_w) 10 m·s^{-1}	175.49	29.2	5.58	35.1
Average wind speed during the temperature drop (V_w) 15 m·s^{-1}	175.49	35.2	–	35.1
Average wind speed during the temperature drop (V_w) 20 m·s^{-1}	175.49	41.2	5.58	35.1
Speed of ice field movement (v_l) 0.5 m·s^{-1}	118.51	29.2	5.58	35.1
Speed of ice field movement (v_l) 1.0 m·s^{-1}	175.49	29.2	5.58	35.1
Speed of ice field movement (v_l) 1.5 m·s^{-1}	259.63	29.2	5.58	35.1
Change in water level (h_0) 0.3 m	175.49	29.2	5.58	35.1
Change in water level (h_0) 0.4 m	175.49	29.2	5.58	35.1
Change in water level (h_0) 0.5 m	175.49	29.2	5.58	35.1
Maximum area ice field at 1% probability (A_l), 50 m^2	175.49	29.2	5.58	35.1
Maximum area ice field at 1% probability (A_l) 100 m^2	248.18	29.2	5.58	35.1
Maximum area ice field at 1% probability (A_l) 150 m^2	303.96	29.2	5.58	35.1

Source: own work.

with a vertical front edge (P_1 or $F_{b,w}$). In the case of a change in water level (h_0) from 0.3 to 0.5 m, no significant influence on ice loads was observed.

The results of the geotechnical stability analysis

Soil parameters used in analysis are presented in Table 5. The results of the stability analysis for overturning and sliding are presented in Figure 8 and Table 6.

Based on the results of the gabion wall check for overturning and sliding, Table 6 shows the overall check results – the wall is satisfactory. The results of the stability analysis for bearing failure are presented in Table 7. Based on the results of the gabion wall check for overturning and sliding, Table 7 shows the overall verification results – bearing capacity of foundation (soil) is satisfactory. The results of deep-seated failure of the retained slope are presented in Table 8.

Table 5. Soil parameters

Sand with trace of fines (S-F), medium dense	
Unit weight	$\gamma = 17.50$ kN·m^{-3}
Stress-state	effective
Angle of internal friction	$\varphi_{ef} = 29.50°$
Cohesion of soil	$c_{ef} = 0.00$ kPa
Angle of friction between structure and soil	$\delta = 0.66°$
Soil	cohesionless
Saturated unit weight	$\gamma_{sat} = 17.50$ kN·m^{-3}
Well graded sand (SW), medium dense	
Unit weight	$\gamma = 20.00$ kN·m^{-3}
Stress-state	effective
Angle of internal friction	$\varphi_{ef} = 36.50°$
Cohesion of soil	$c_{ef} = 0.00$ kPa
Angle of friction between structure and soil	$\delta = 0.66°$
Soil	cohesionless
Saturated unit weight	$\gamma_{sat} = 20.00$ kN·m^{-3}

Source: own work.

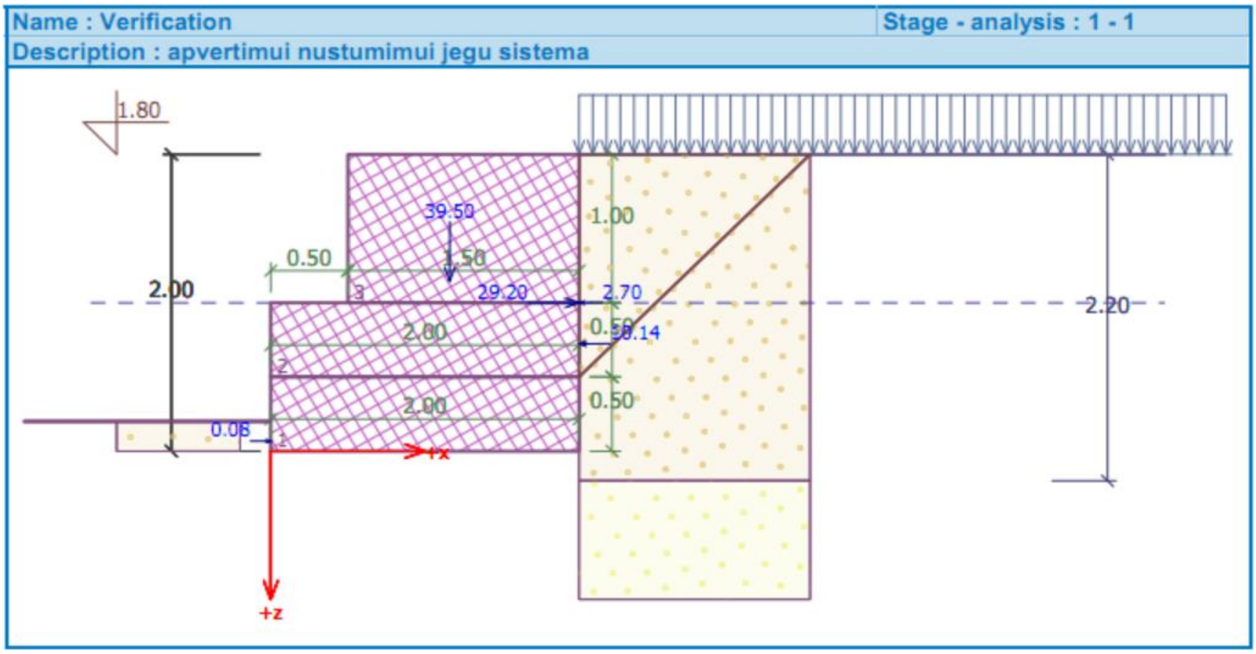

Fig. 8. The calculation scheme for verification of wall

Source: own work.

Table 6. The gabion wall check for overturning and sliding

Check for overturning stability		Check for slip	
Resisting moment (M_{res})	53.91 kN·m^{-1}	Resisting horizontal force (H_{res})	20.42 kN·m^{-1}
Overturning moment (M_{ovr})	13.53 kN·m^{-1}	Active horizontal force (H_{act})	11.94 kN·m^{-1}
Wall resistance against overturning is satisfactory		Wall resistance against slip is satisfactory	

Source: own work.

Table 7. The gabion wall stability analysis for bearing failure

Eccentricity verification		Verification of bearing capacity	
Norm, force 53.47 kN·m^{-1}	Maximum eccentricity of normal force e = 0.000 Maximum allowable eccentricity e_{alw} = 0.333	Maximum stress at footing bottom σ = 26.74 kPa	Bearing capacity of foundation soil R_d = 35.71 kPa
Eccentricity of the normal force is satisfactory		Bearing capacity of foundation soil is satisfactory	

Source: own work.

Table 8. Slope stability verification (using Bishop method)

Forces		Moments	
Sum of active forces (F_a)	35.21 kN·m^{-1}	Sliding moment (M_a)	151.74 kN·m^{-1}
Sum of passive forces (F_p)	57.37 kN·m^{-1}	Resisting moment (M_p)	247.25 kN·m^{-1}

Source: own work.

Based on the results of the gabion wall check for slope stability verification, Table 8 shows that slope stability is acceptable – factor of safety (F_S) = 1.63 > 1.50 (minimum required F_S).

CONCLUSIONS

1. The results of wave load calculation show that the gabion retaining wall for shore protection is subject to a horizontal projection of wave force (P_x) equal to 6.13 kN·m^{-1} and vertical projection of wave force (P_z) equal to 7.72 kN·m^{-1}. The magnitude of the calculated hydrodynamic forces shows the possible reason of the structural deformations and settlement of former reinforced concrete retaining wall.
2. Based on the results of the ice loading calculations, it has been found that:
   – The changes of ice thickness directly affect calculation results of all types of the ice loads.
   – The changes of average wind speed during the temperature drop (V_w) have impact on values of horizontal linear loads on structures due to the ice cover thermal expansion effect (P_3 or q).
   – The changes of speed of ice field movement (v_l) from 0.5 m·s^{-1} to 1.5 m·s^{-1} and ice field maximum area (A_l) from 50 m^2 to 150 m^2 directly affect the calculation results of the horizontal load of moving ice fields on a structure with a vertical front edge (P_1 or $F_{b,w}$).
   – In the case of a change in water level (h_0) from 0.3 m to 0.5 m, no significant influence on ice loads was observed. The calculated ice loads have direct impact on stability of the gabion retaining wall.
3. The numerical results reveal good geotechnical stability – calculations of the stability of a typical gabion retaining wall in case of overturning and sliding show that the wall resistance against overturning and slip is satisfactory. The evaluation of the gabion retaining wall base strength according to the loss of load-bearing capacity shows that the eccentricity of the normal force is satisfactory and the bearing capacity of foundation soil is satisfactory. Overall verification shows that the bearing capacity of foundation (soil) is satisfactory. Calculations of the deep seated failure of the retained slope show that the slope stability is acceptable.
4. The results of wave and ice loads calculation and geotechnical stability analysis show that structures formed from gabions should be able to resist different types of loads and are suitable for protection of lake coastline.

Authors' contributions

Conceptualisation: R.Š. and I.A.; methodology: R.Š. and R.B.; validation: R.Š., I.A. and K.G.; formal analysis: R.Š. and M.K.; investigation: R.Š.; resources: I.A. and M.K.; data curation: K.G. and M.K.; writing – original draft preparation: R.Š.; writing – review and editing: I.A. and M.K.; visualisation: K.G.; supervision: R.Š.

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

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ZASTOSOWANIE GABIONÓW DO PROJEKTOWANIA KONSTRUKCJI OCHRONY WYBRZEŻA W JEZIORACH

STRESZCZENIE

W wypadku zbiorników wodnych i jezior o dużych obszarach droga spływu fal jest również duża, co powoduje powstawanie wysokich fal w kierunku wiejącego wiatru. Fale te intensywnie niszczą brzeg jeziora lub zbiornika wodnego. Innym intensywnym czynnikiem erozji wybrzeża jest lód. Do ochrony wybrzeża zbiorników wodnych stosuje się wiele środków inżynierskich: w wypadku jezior są to płyty żelbetowe, bloki, wysięgniki, systemy komórkowe (geosyntetyki) itp. W niniejszej pracy przeanalizowano zerodowaną linię brzegową, przekształconą poprzez zainstalowanie konstrukcji zabezpieczającej wybrzeże z wykorzystaniem konstrukcji gabionowych. Gabiony są przeznaczone do ochrony brzegów i skarp przed szybkim spływem wody (prędkość wody powyżej 5 $m \cdot s^{-1}$) oraz uderzeniami lodu. Projektuje się je według zasad geotechnicznych, oceniając stateczność zgodnie z granicznymi sytuacjami projektowymi określonymi w Eurokodzie 7 (EN 1997-1). Celem niniejszej pracy jest zilustrowanie przypadków obciążeń falami i lodem oraz geotechnicznych sytuacji projektowych, ocenianych w projekcie konstrukcji ochrony wybrzeża, która jest wykonana z gabionów.

Słowa kluczowe: struktury ochrony wybrzeża, fale i uderzenia lodu, gabiony, geotechniczne sytuacje projektowe

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REVIEW PAPER

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MOTTAINAI IN CIVIL ENGINEERING – A MESSAGE FROM JAPAN

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ABSTRACT

This article examines the impact of Japan's *mottainai* concept on civil engineering practices, focusing on the waste of materials, financial resources, and harmonisation of structures with the environment. The authors highlight the global challenges of environmental and social imbalances in the context of global warming. The Japanese concept of *mottainai* is presented as the key to shaping the civil engineering approach. The inefficient use of raw materials was analysed in terms of material waste. A transition to a closed-loop economy is recommended, emphasising the need for resource efficiency. In the context of financial resources, the need for efficient budget allocation and project management is emphasised. The section on harmonising structures with the environment focuses on aesthetics, environment, sustainable mobility, and an integrated approach to urban planning. Civil engineering projects should combine functional efficiency with respect to the environment, and the *mottainai* concept can be a tool for achieving sustainability in civil engineering. Innovative solutions, such as intelligent energy management systems, are recommended to improve construction efficiency.

Keywords: civil engineering, material wastage, sustainability, construction, closed-loop economy

INTRODUCTION

Global studies suggest that humans have significantly upset the balance between nature and society, and that they should be aware of the environmental impact of their actions, given the consequences of global warming for the entire world (Kimata & Takahashi, 2020; Kimata & Takahashi, 2022; Syvitski et al., 2022). As people change their lifestyles, values, places of residence, and means of transportation, civil engineering must adapt to these changes in order to avoid serious problems related to waste – called *mottainai* in Japanese – and climate change. Speaking of *mottainai* in civil engineering, it's about adapting to the changes taking place in the world, such as how and where people will live and how people and goods will be transported in the future (Tokat & Taş, 2022).

The Japanese expression *mottainai* can be translated as 'What a waste!' or 'Don't waste!'. *Mottainai* means much more. It expresses concern or regret for what has been wasted because its intrinsic value has not been properly utilised. Buddhism and Japan's indigenous religion, Shinto, are integral parts of the Japanese psyche, which is why the non-human world is experienced and lived in everyday life. In the Japanese worldview, everything in nature is endowed with spirit; each individual existence is dependent on others, and everyone is interconnected in an ever-changing world (Sato, 2017; Kinefuchi, 2018; Rayhan, 2023).

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Currently, *mottainai* is reflected in Japan's approach to environmental protection and sustainability. This term is used to promote resource conservation and discourage waste. Japanese people are taught from an early age to conserve water, electricity, and other precious resources (Rayhan, 2023). Japan's experience can serve as a model for other regions of the world to improve their practices and achieve sustainability goals. By analysing the Japanese model, valuable lessons can be learned and applied to many European countries, especially Central Europe. Japan's success in instilling these principles from an early age positioned it as a model for global sustainability. When applying the *mottainai* experience to European countries, particularly Central Europe, cultural nuances must be considered. Adaptation involves collaborative efforts, including awareness campaigns and policy initiatives, tailored to the unique challenges and opportunities in Central Europe. By fostering cross-cultural exchanges and leveraging successful waste management practices, the aim is to cultivate a shared commitment to sustainability on a global scale.

Figure 1 illustrates how the concept of *mottainai* contributes to a more comprehensive approach to the Sustainable Development Goals (SDGs). In comparison to the traditional '3Rs' of 'reuse, reduce, and recycle' (Mohammed, Shafiq, Abdallah, Ayoub & Haruna, 2020), *mottainai* incorporates a fourth 'R'of 'respect' (Xiang & Li, 2021). This addition emphasises cultural and ethical dimensions, enriches the sustainability framework, and fosters a deeper connection between individuals and the environment.

The concept of *mottainai* has influenced environmental campaigns in Japan and beyond, for example through the work of the late Nobel laureate and founder of the African Green Belt Movement, Wangari Maathai (Suzuki, 2013; Kinefuchi, 2018; Mutua & Omori, 2018). The relationship between resource use and societal well-being extends in several directions. Inadequate and unevenly distributed resources can lead to political and economic conflicts, and environmental problems (McManus Warnell & Umeda, 2019). The role of civil engineering in the use of natural resources is one of the most important activities for achieving a sustainable future.

The mission of civil engineering is to build infrastructure that serves society. Therefore, civil engineers must pay attention to all the factors that can affect people's lives, identify the interactions between these factors, and understand the world as an integrated system comprising all these interactions (Terzano, 2023). In other words, we need to think in terms of systems theory. Many projects currently planned or underway will still be in use by 2050. Therefore, civil engineers must take the lead in carefully considering the future of civil engineering.

Civil engineering plays a key role in shaping (transforming) the environment, and the concept of *mottainai* can be a valuable lens through which the effectiveness and sustainability of engineering practices can be evaluated. This article focuses on the Japanese cultural values of *mottainai* (referring to the avoidance of undesirable actions), taking into account both material and financial resources, as well as the long-term impact of building structures on their surroundings – the environment.

Fig. 1. *Mottainai* – A message from Japan to the world

Source: Kimonoboy (2023) modified by the authors.

WASTAGE OF MATERIALS AND MACHINERY

Concerns about the devastating environmental impacts of construction processes (e.g. energy and material consumption, waste and dust generation, and air and water pollution) have led to increased awareness of the need for sustainable construction practices (Son, Kim, Chong & Chou, 2011). In civil engineering, the judicious use of materials and machinery is of paramount importance for sustainable and responsible construction practices (Son et al., 2011; Terzano, 2023). *Mottainai* highlights the waste that occurs when these resources are used inefficiently (Xiang & Li, 2021).

Inefficient use of materials

Currently, unprecedented amounts of fossil material minerals are extracted and consumed from the Earth's crust (Stephan & Athanassiadis, 2018). The global extraction of non-metallic minerals (gravel, sand, clay, limestone, and gypsum) reached approximately 35 billion tonnes in 2010. Sand and gravel accounted for the bulk of the world's non-metallic mineral extraction in 2010 (40.8% gravel and 31.1% sand), (Miatto, Schandl, Fishman & Tanikawa, 2017; Ghaffar Burman & Braimah, 2020). The main end-users of this consumption are infrastructure investments and major construction projects. The transition to a closed-loop economy, in which production flows can be reintegrated as secondary resources, is a promising solution for the construction industry (Stephan and Athanassiadis, 2018; Ghaffar et al., 2020).

Wastage of material often results from poor planning, inaccurate estimates, and inadequate recycling practices. The waste of materials as a consequence of the inefficient use of materials increases the cost of investment (construction projects), negatively impacts the environment (environmental degradation), and increases the carbon footprint.

To minimise the environmental impact, it is essential to implement advanced modelling and simulation tools to accurately estimate materials (Keulemans, Harle, Hashimoto & Mugavin, 2020), use sustainable, natural (Fig. 2), and recycled materials (Murray, 2019), and integrate sustainable construction principles to reduce the environmental impact of materials and waste generation (Ghaffar et al., 2020; Mohammed et al., 2020; Udomsap & Hallinger, 2020).

Suboptimal placement of machines

Construction work often involves the use of heavy machinery, and its inefficient deployment can lead to a significant waste of resources (Lewis, Karimi, Shan & Rasdorf, 2019; Rashid & Louis, 2019; Huang, Fan, Shen & Du, 2021). Errors in the use of machinery, including overreliance on heavy equipment, lack of maintenance, and inadequate operator training, have a direct impact on project timelines, costs, and environmental impacts.

To optimise construction work, the regular maintenance of machinery and equipment is recommended to ensure optimal machine performance and durability. Important elements include training programs for machine operators to increase productivity and reduce errors and the integration of advanced technologies, such as the use of building information modelling (BIM), to optimise machine placement and project management planning (Akinosho et al., 2020; Rahimian, Seyedzadeh, Oliver, Rodriguez & Dawood, 2020).

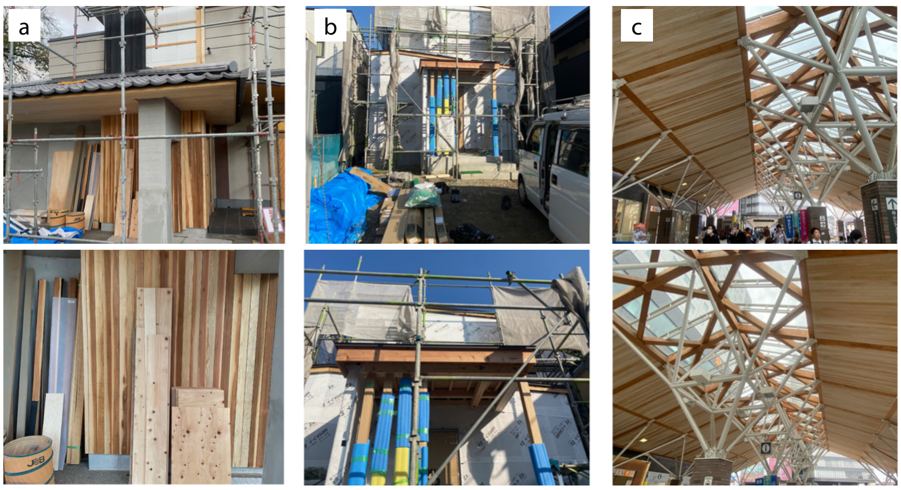

Fig. 2. Use of sustainable and natural materials in construction: a – residential house; b – office building; c – train station

Source: photos by Magdalena Daria Vaverková, Okayama, 2023.

Environmental consequences

A key issue is the environmental impact of the waste materials and machinery. Improper disposal and management of construction waste, machine emissions and construction activities contribute to environmental degradation (Jalaei, Zoghi & Khoshand, 2019; Barbhuiya & Das, 2023). This underscores the need for a holistic approach to mitigate these consequences and promote environmental responsible construction practices (Pham & Kim, 2019; Shurrab, Hussain & Khan, 2019; Avotra, Chenyun, Yongmin, Lijuan & Nawaz, 2021).

It is important to implement waste management plans that encourage recycling and minimise landfilling (Joensuu, Edelman & Saari, 2020; Kabirifar, Mojtahedi, Wang & Tam, 2020). Use of low-carbon and energy-efficient machinery and recycling materials to reduce carbon footprint.

A detailed understanding of the waste of materials and machinery in civil engineering, setting it in the context of *mottainai*, should involve analysing the various dimensions of inefficiency (Terzano, 2023). There should be a dialogue on sustainable construction practices aiming for a future in which resource use is seamlessly combined with human responsibility for the environment.

WASTAGE OF FINANCIAL RESOURCES

In civil engineering, efficient allocation of financial resources is integral to project success (Pan & Zhang, 2021). Financial resources are often allocated to various elements of a construction project, ranging from materials and labour to equipment and contingency funds. The consequences of misallocating budgets such as cost overruns, delays, and reduced quality have a major impact on construction projects. Inefficient financial management has a negative impact on project performance, underscoring the need for precise budget planning and risk identification (Lyu, Sun, Shen & Zhou, 2019; Siraj & Fayek, 2019; El khatib et al., 2022).

It is essential to implement robust project management software to ensure accurate budget tracking and analysis. Regular audits should be conducted to ensure adherence to budget allocations and timely identification of discrepancies. It is also necessary to create contingency funds for unforeseen circumstances, limiting disruption to the overall financial plan.

HARMONISATION OF THE BUILDING WITH THE SURROUNDINGS

In today's world, where climate change is becoming increasingly obvious, the harmonisation of buildings with the environment is becoming a key element of sustainable development. In the concept of *mottainai*, harmonisation with the environment in civil engineering projects can be seen as a deeper understanding and respect for the relationship between people and the environment (Bao, Lee & Lu, 2020; Berglund et al., 2020). Vitková and Lemak (2021) emphasised the importance of a thoughtful strategy for this harmonisation, especially in urban environments, to mitigate negative climate impacts. Saroop and Allopi (2013) further emphasised the role of engineers in the design of environmentally sustainable infrastructure and the use of green technologies. Zavadskas, Vilutienė and Tamošaitienė (2017) emphasised the need for sustainable construction processes to minimise environmental impacts. Together, these studies emphasise the importance of harmonising construction with the environment in civil engineering projects, and the potential of this approach to contribute to sustainable development.

Aesthetic and environmental aspects

Civil engineering projects should not only meet functional requirements, but also harmoniously blend with the surrounding landscape. The aesthetic aspects of designs are important for integration with the surroundings (Shahi, Esfahani, Bachmann & Haas, 2020; De Medici, 2021; Lucchi, Baiani & Altamura, 2023). Designers and engineers should consider the local landscape features, history, and culture to avoid compromising the integrity of their surroundings. Gluch (2005) emphasises the need for construction to move away from product-centered action toward process-centered action, which is consistent with the concept of *mottainai*. Both Voskresenskaya, Vorona-Slivinskaya and Panov (2018), and Opoku, Agyekum and Ayarkwa (2019) emphasise the importance of environmental sustainability in construction, Opoku et al. (2019) mainly identifies factors such as customer expectations, and Voskresenskaya, Vorona-Slivinskaya and Panov (2018) emphasises the need for innovative approaches to environmental protection. Subbotin (2019) additionally draws attention to the role of building materials and technologies in achieving both architectural and environmental goals, which can be linked to *mottainai* and efficient use of resources and aesthetic appeal (Fig. 3).

Fig. 3. Examples of efficient use of resources and aesthetic appeal of interior architecture using Okayama University facilities as an example

Source: photos by Magdalena Daria Vaverková, Okayama, 2023.

In the context of *mottainai*, infrastructure design must not only be purely functional but also respect the beauty of the surrounding nature (Jimura, 2023; Terzano, 2023). The aesthetic aspects of design become an expression of respect for nature, just as the Japanese concept of *mottainai* expresses care for what has been given to us.

'Kengo Kuma and Associates undertook the development of a wooden classroom for Okayama University in Japan. The project was assembled with a specific focus on enhancing education on wood construction techniques and providing an informative learning environment for students pursuing studies in this field. This "Wooden Classroom" concept for Okayama University illustrates the potential of timber construction. Beyond its role as an educational space, the project encourages reflection on sustainable architectural innovations by involving students and observers in envisioning eco-friendly design solutions. Architects integrated a transparent glass canopy and fused Cross Laminated Timber (CLT) components with steel elements to emphasize the versatility of wood in combination with other materials' (Petridou, 2023). Figure 4 showcases the architectural innovation in the development of a wooden classroom. This project, designed to advance education on wood construction techniques, emphasises creating an immersive and informative learning environment for students specialising in this field. This depiction underscores the potential of timber construction in promoting sustainable architecture and educational initiatives, making it a noteworthy case study for eco-friendly design and construction practices.

Fig. 4. Kengo Kuma's pillar-free wooden classroom boosts eco-friendly designs at Okayama University

Source: photos by Magdalena Daria Vaverková, Okayama, 2023.

Successful harmonisation with the environment requires consideration of a project's impact on ecosystems and sustainability. The use of green technologies, such as eco-friendly building materials (Jimura, 2023), natural water treatment systems, and green roofs, can minimise the negative impact of infrastructure on the local environment (Shi & Liu, 2019; Liu & Li, 2023; Wamane, 2023). In addition, strategies that take into account the rehabilitation and development of areas after construction work is completed are key to restoring ecological balance.

Mottainai formulates a call to avoid wasting resources, and sustainable practices in civil engineering are a perfect reflection of this approach. The selection of environmentally friendly materials, sustainable transportation solutions and diligence in land use planning are all actions that eliminate wasteful use of resources.

Integrated approach to urban planning and sustainable mobility

Integrated spatial planning considers the needs of both people and nature to be key to sustainable development (Huser, 2011; Liu & Zhou, 2021). This approach requires the full integration and assessment of environmental, social, and economic issues (Eggenberger & Partidário, 2000). It also involves harmonising the natural environment in architectural spaces, as seen in the work of Frank Lloyd Wright (Emelianov, Bakaeva & Zuleta, 2019; Vaughan & Ostwald, 2022). Integrating ecosystem services into urban planning can help protect key habitats and support the provision of these services (Grêt-Regamey, Altwegg, Sirén, van Strien & Weibel, 2017).

Integrating sustainability principles into construction projects, including the maintenance of natural ecological corridors and a balanced urban natural environment, is crucial for improved project implementation (Ochieng, 2014). Effectively planned green infrastructure can contribute to social well-being and sustainable urban development (Plata, Elías Orozco & Villaseñor, 2019). The strategy of building roads as 'aesthetic greenways' in China, emphasising the protection of natural habitats and the promotion of local tourism and economic growth, can serve as a model for balancing environmental and socioeconomic needs (Cheng, Lv, Zhan, Su & Cao, 2015). The construction of urban ecological corridors, which require a spatial approach to balance ecological protection and economic development, is particularly important for sustainable urban development (Peng, Zhao & Liu, 2017).

Civil engineering projects should focus on sustainable mobility and accessibility. Creating bicycle paths, developing public transport systems, and promoting pedestrian zones are elements that not only reduce the negative impact on the environment but also create friendly and accessible spaces for the community (Fig. 5).

Tiwari (1999) underscored the necessity of establishing secure infrastructure for non-motorised modes, such as pedestrians and cyclists, to enhance the effectiveness of public transport. Building on this, Curtis (2008) highlighted the significance of sustainable accessibility and advocated a fundamental shift in urban development to bolster both efficient public and private transport systems. Similarly, Giduthuri (2015) and Un-Habitat (2015) emphasised the importance of urban planning and design, which prioritise accessibility and sustainable transport modes, such as cycle paths and pedestrian zones. Collectively, these studies emphasise the pivotal role of sustainable mobility and accessibility in civil engineering projects, not only in mitigating environmental impacts, but also in crafting inclusive and efficient urban spaces.

In the spirit of *mottainai*, integrated spatial planning has become a joint effort between society and the natural environment.

Education and social participation

Aboelata, Ersoylu and Cohen (2011), and Kamel and Lim (2012) emphasised the importance of community involvement in sustainable engineering projects, emphasising the need for engineers to understand and address the problems of local communities. This can be achieved through the development of specific competencies as well as the use of appropriate engagement mechanisms. Johnston, Caswell and Armitage (2007) further emphasised the role of education in increasing environmental awareness among engineers, suggesting the use of real projects to implement sustainable

Fig. 5. Sustainable mobility and availability of bicycle parking in Japan

Source: photos by Vaverková, 2022/2023, Igor Vaverka, 2023.

development principles. Fernandes, Rangel, Alves and Neto (2019), and Keirl (2020) highlighted the role of design and technology education in promoting a sustainable global future. Collectively, these studies highlight the importance of community education and engagement in achieving environmental harmonisation in engineering and architectural design.

In the context of *mottainai*, the harmonisation of buildings with their surroundings is not only an end in itself, but also a means to avoid waste in a wide range of engineering and architectural activities. It is an expression of concern for all aspects of the environment, where resources are valued, and harmony between humans and nature is the basic principle of development (Maltseva, Kaganovich & Lorentz, 2018; Khaing, 2020). Moreover, the role of construction and architecture in promoting unity with nature is emphasised, with the design of environmentally friendly spaces and improvement of the microclimate being key aspects of this harmonisation (Emelianov et al., 2019).

FEATURES AND PERFORMANCE IN THE CONTEXT OF *MOTTAINAI*

In the context of *mottainai*, the functions and performance of civil engineering projects have become key aspects that combine efficiency with respect to resources and the environment. Civil engineering projects should be guided by not only functionality but also sustainable design goals. The functional value of the structures should be achieved with minimal environmental impact. The application of innovative solutions such as smart energy management systems or efficient lighting systems can enhance the functional performance of buildings (Gagnon, Leduc & Savard, 2014; Pan & Zhang, 2021; Kim et al., 2021).

Implementing energy-efficient solutions, in line with the concept of *mottainai*, is a key aspect of sustainable development. Both Zavalani (2011) and Gagliano (2014) emphasise significant energy savings achievable through the adoption of energy management systems and alternative energy generation and conservation systems in buildings. Mutani and Vicentini (2015) further underscored the importance of local authorities in promoting and encouraging private investments in energy-efficient solutions, especially in urban areas. However, Feng (2019) highlighted the challenges associated with implementing these solutions in warm climates, suggesting the need for educational programs, enhanced regulations, and financial incentives. Collectively, these studies underscore the potential of energy-efficient solutions to reduce operational costs and environmental impacts. They also emphasised the need for supportive policies and development strategies, taking into account the broader utilisation of renewable energy sources such as solar panels, heat pumps, and small wind turbines. Solutions based on closed-loop systems, particularly for the utilisation of water and certain types of waste, are also crucial.

CONCLUSIONS

In the context of civil engineering, the concept of *mottainai* has become a guiding philosophy for construction practices in a sustainable and responsible manner, avoiding waste. By analysing the aspects of material and machine waste, improper allocation of financial resources, and harmonisation with the environment, architects and civil engineers can achieve investment efficiency goals while respecting the environment. *Mottainai* can become a key opportunity for the development of civil engineering and sustainable construction. By focusing on minimising resource waste, applying sustainable construction practices, and integrating projects with the natural and social environment, civil engineering can be not only efficient, but also in line with the spirit of the *mottainai* concept. It requires collective efforts from society, business, and science directed towards a future where human development harmonises with environmental protection, and resources are valued and used with discretion. Such efforts can improve human living conditions and mitigate the effects of climate change on Earth.

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Authors' contributions
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MOTTAINAI W INŻYNIERII LĄDOWEJ – PRZESŁANIE Z JAPONII DLA ŚWIATA

STRESZCZENIE

Artykuł analizuje wpływ japońskiej koncepcji *mottainai* na praktyki inżynierii lądowej, skupiając się na marnotrawstwie materiałów, zasobów finansowych i harmonizacji budowli z otoczeniem. Autorzy podkreślają globalne wyzwania związane z zaburzeniem równowagi między środowiskiem a społeczeństwem w kontekście globalnego ocieplenia. Japońskie pojęcie *mottainai* jest przedstawione jako kluczowe w kształtowaniu podejścia inżynierii lądowej. W obszarze marnotrawstwa materiałów analizuje nieefektywne wykorzystanie surowców. Zaleca się przejście na gospodarkę o obiegu zamkniętym, podkreślając konieczność efektywnego gospodarowania zasobami. W kontekście zasobów finansowych podkreślono potrzebę efektywnej alokacji budżetów i zarządzania projektami. Sekcja dotycząca harmonizacji budowli z otoczeniem skupia się na aspektach estetycznych, środowiskowych, zrównoważonej mobilności i zintegrowanym podejściu do planowania przestrzennego. Projekty inżynierii lądowej powinny łączyć efektywność funkcjonalną z poszanowaniem dla środowiska, a koncepcja *mottainai* może stanowić narzędzie do osiągnięcia zrównoważonego rozwoju w inżynierii lądowej. Zaleca się stosowanie innowacyjnych rozwiązań takich jak inteligentne systemy zarządzania energią w celu poprawy wydajności konstrukcji.

Słowa kluczowe: inżynieria lądowa, marnotrawstwo materiałów, zrównoważony rozwój, budownictwo, gospodarka o obiegu zamkniętym

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