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PROMOTING ENVIRONMENTAL SUSTAINABILITY IN CONSTRUCTION: EXPLORING IMPLEMENTED SOLUTIONS THROUGH CASE STUDIES

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ABSTRACT

It is imperative to take pro-ecological actions that are beneficial to health, as well as adopt sustainable development practices in the face of the current environmental challenges facing humanity. It is crucial that environmental protection is implemented by all people on Earth, because the future is worrying – especially for what will be left for future generations. Green building solutions are being implemented worldwide, but not always in an appropriate manner. All green architecture integrates sustainable development and conservation, regardless of location. This article summarises and characterises the concept of the 6E (economic, energy-efficient, ecological, elastic, aesthetic, ergonomic) ecological building concept and the 3R (reduce, reuse, recycle) principle. It also presents an analysis of two ecological buildings in Poland. The first is a wooden building located in the village of Podgać, which serves as an example of combining modern design and ecology. It was built in harmony with nature and blends in with the natural environment of the forest. A half-timbered house in the village of Jarzębia Łąka is the second example where traditional construction, modern technical solutions and environmental protection come together. The presented project examples were examined in terms of ecological building principles and then compared with the 6E concept and the 3R principle. This paper presents a comprehensive study of two distinct eco-friendly building structures. The investigation covers technical characterisation, compliance with the 6E concept, comparison of ecological efficiency, and conclusions with recommendations. The Dom Baby Jagi [Baba Jaga House] in the village Podgać showcases a harmonious blend of simplicity, functionality, and economy, utilising wood with insulation for year-round habitation. It integrates renewable energy sources and rainwater harvesting, contributing to its ecological sustainability. Meanwhile, the half-timbered building in Jarzębia Łąka employs clay-straw bricks for construction, emphasising economic and environmental benefits with vapour-permeable walls and efficient insulation. Both structures exemplify ergonomic design, eco-friendly construction practices, and aesthetic integration with their natural surroundings. These findings underscore the importance of incorporating environmentally conscious solutions in modern architecture to address contemporary environmental challenges and promote sustainable development.

Keywords: eco-friendly construction, sustainable development practices, green building solutions, 6E concept, 3R principle

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INTRODUCTION

The subject of ecological construction is multifaceted and encompasses various dimensions. The term 'green building' refers to structures made from healthy and energy-efficient materials and solutions, employing energy-efficient and environmentally non-destructive construction methods and techniques. Such construction is more integrated with nature and significantly less polluting to the natural environment compared to conventional buildings (Walenda & Starczyk-Kołbyk, 2022).

The 6E concept is based on the idea of increased energy efficiency in construction. Nowadays, there is a growing interest in the energy industry and academia to apply advanced energy, exergy, exergo-economy, exergo-environment, emergo-economy and emergo-environmental analyses – ranging from 3R to 6E analyses – to achieve better solutions (Khani, Manesh & Onishi, 2023). This concept involves the design and construction of buildings with the aim of minimising energy consumption and reducing negative environmental impact (Şahin & Kılıç, 2024). It encompasses all aspects of the building, including energy efficiency, construction and operational costs, a sustainable approach to the natural environment, user comfort, and architectural aesthetics (Fig. 1). The 6E concept encompasses six key aspects:

(i) Economic – ensuring that the project and construction are achievable within the available budget, while reducing long-term operating costs.
(ii) Energy efficient – ensuring efficient use of energy during construction and operation of the building, including strategies for insulation, ventilation, lighting and heating systems.
(iii) Ecological – minimising the building's impact on the natural environment by using ecological materials, reducing carbon dioxide emissions, conserving natural resources, and protecting local ecosystems.
(iv) Elastic – using prefabricated and other ready-made components, ensuring modularity.
(v) Aesthetic – addressing the design and finishing aspects of the building to create an attractive and harmonious environment that is pleasing to the eye and in keeping with its surroundings.
(vi) Ergonomic – providing comfort and functionality for users through ergonomics, accessibility for people with disabilities, and efficient use of space.

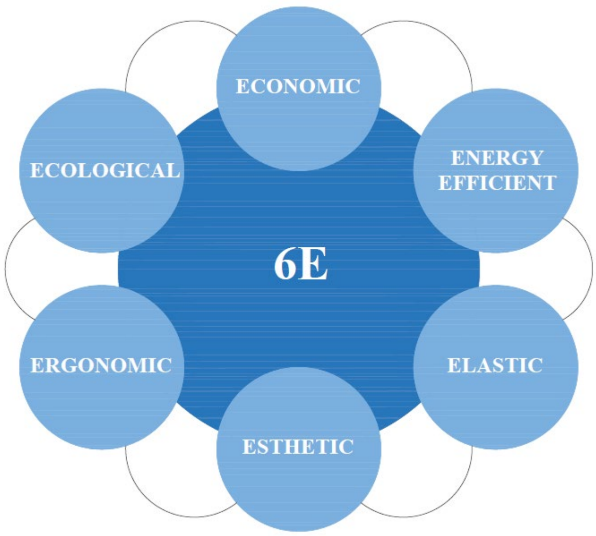

Fig. 1. Schematic representation of the 6E concept

Source: own work.

The 3R principle (reduce, reuse and recycle), also known as the "waste management hierarchy" (Coalition of 5 Fractions, 2022), is in perfect alignment with ecological construction (Zhang et al., 2022; Vaverková, Matsui & Vaverka, 2023; Victar, Perera, Palihakkara & Dewagod, 2023). Reduce, reuse, and recycle, are three components of the components of the 3R concept. Reduce means selecting and using factors that reduce the amount of the waste produced. Recycle means using waste as a resource. Reuse means using waste that is still in a usable condition. Reduce is the most important factor compared to reuse and recycle for minimising waste (Aadal, Rad, Fard, Sabet & Harirchian, 2013). Waste reduction through the 3Rs is one of the most effective steps the construction industry can take toward sustainable waste management (Mitra & Datta, 2014). When reuse and recycle practices are applied to the large amount of construction waste generated at construction sites, such practices lead to the achievement of sustainable development goals and often to the development of new products (Schroeder, Anggraeni & Weber, 2019).

As Skowroński observed in the latter half of the 20th century, a waste management system was developed, which is simplified and based on the 3R principle: reduce, reuse, and recycle (Fig. 2). The objective is to halt further environmental degradation (Skowroński, 2015). When purchasing building materials, it is important to choose wisely and buy only the necessary amount, avoiding unnecessary purchases. The reduce principle necessitates that packaging be biodegradable. During the construction phase and throughout the operational lifespan of the building, it is encouraged to exercise creativity in identifying potential reuse opportunities for materials. Recycle, the final stage of the 3R principle, involves the segregation of waste during construction and building use, allowing for the recycling of materials into new products. To preserve and improve environmental quality, protect human health, and ensure the prudent, efficient, and rational use of natural resources, environmentally friendly actions are already being taken with the aim of saving our environment (Ulewicz, 2021).

The US Census Bureau (2024) indicates that the global population has surpassed 8 billion individuals on 15 November 2023. The global population has been steadily increasing since the end of World War II (Ganivet, 2020; Vollset et al., 2020). Projections suggest that this upward trend will continue, and it can

Fig. 2. Schematic representation of the 3R principle

Source: own work.

be reasonably assumed that there will also be an increasing demand for housing. Construction, in conjunction with the production of building materials, exerts a profound influence on the natural environment (Maraveas, 2020; Tang, Li, Tam & Xue, 2020). The expansion of the global population has intensified the urgency for environmental stewardship among humanity. Developers with a long-term perspective should prioritise ecological solutions for all aspects of construction and subsequent building operations (Kang, Zhang, Zhu & Zhang, 2021; Sood, Kumar, Jena & Joshi, 2023). Such action helps to reduce, among other things, the emission of carbon dioxide into the atmosphere.

The term ecological construction is a broad concept that encompasses various technologies and building materials. Among the eco-friendly materials used in construction are: (i) natural materials, including clay, sand, stone, rocks, straw, hay, flax, hemp, and wood, are employed in the construction industry; (ii) ceramic materials, such as bricks and expanded clay aggregate, are also utilised; (iii) concrete materials, including cellular concrete, are also used; (iv) synthetic materials, such as silicates, are also employed in the construction industry; additionally, (v) glass and organic materials, including wastepaper and fibres derived from it (Kietliński, 2015; Silva, Kim, Aguilar & Nakamatsu, 2020; Sharma, 2020; Amran et al., 2021).

The objective of this article is to conduct a comparative analysis of two distinct ecological buildings in terms of their compliance with the principles of ecological construction, with a particular focus on the 6E concept and the 3R principle.

MATERIAL AND METHODS

The study focused on two different building structures: (i) a wooden structure located in the village of Podgać, and (ii) a straw and clay half-timbered structure located in the village of Jarzębia Łąka.

The investigation included several key areas:

(i) Technical characterisation: This included detailed descriptions of the structure, building materials, and construction technologies used in both buildings. The wooden building in Podgać and the half-timbered building in Jarzębia Łąka were examined for their architectural features, material compositions, and construction methods.

(ii) Conformity assessment: The study analysed the extent to which the surveyed buildings complied with the principles of the 6E concept, which includes energy efficiency, ecological use of materials and technologies, structural adaptability, architectural aesthetics, ergonomic design, and economic viability. In addition, the evaluation included an assessment of how well the buildings complied with the 3R principle of the waste management hierarchy, focusing on reduction, reuse and recycling practices.

(iii) Comparison of environmental performance: A comprehensive comparison of the environmental performance of the buildings was conducted, evaluating factors such as energy consumption, carbon dioxide emissions, waste generation, and other relevant environmental indicators. This comparative analysis provided insights into the overall environmental efficiency of each building.

(iv) Conclusions and recommendations: Based on the results of the analysis, conclusions were drawn regarding the environmental performance and overall sustainability of the buildings studied. In addition, recommendations were proposed to improve their environmental performance and optimise their environmental impact.

RESULTS AND DISCUSSION

There is a noticeable shift in modern construction practices towards the comprehensive integration of ergonomic principles at every stage of the building lifecycle, from initial design and construction to ongoing operation and maintenance (Awad, Guardiola & Fraíz, 2021; Sutarja & Putra, 2022). This multifaceted approach not only emphasises the importance of creating spaces that optimise comfort and functionality, but also underscores the importance of prioritising the safety and well-being of both construction workers and eventual occupants (Becerik-Gerber et al., 2022; Engelen, Rahmann & de Jong, 2022). By carefully considering ergonomic factors throughout the planning and execution phases of a construction project, stakeholders can proactively address potential challenges and mitigate risks associated with physical strain, injury or discomfort (Riva, Rebecchi, Capolongo & Gola, 2022). In addition, the seamless incorporation of ergonomic design elements contributes to increased productivity, efficiency, and overall user satisfaction, thereby fostering a conducive environment for work, leisure, and daily activities within the built environment. As such, the overarching goal of integrating ergonomic solutions into contemporary building endeavours transcends mere compliance with regulatory standards; rather, it epitomises a commitment to fostering sustainable, human-centred spaces that promote optimal performance and well-being for all stakeholders.

Baba Jaga House

The initial example under consideration is a wooden structure situated in the Podgać region, surrounded by a pine-birch forest (Fig. 3). The image of the wooden building in the Podgać village illustrates the symbiotic relationship between the structure and its natural surroundings. The case study concerns a modest dwelling, covering a mere 35 m^2 of building area, yet the available space has been optimally utilised.

Dom Baby Jagi [Baba Jaga House], designed by the Polish architectural firm Pole Architekci, exemplifies a harmonious integration of simplicity, functionality, and economy. The building is supported by nine concrete foundation columns and offers a living space of 35 m^2. The use of wood with insulation allows for year-round habitation. Its unconventional roof shape gives it a modern character, while the glass façade opens onto

Fig. 3. View of the façade of a wooden building in Podgać, Poland

Source: photos by Aneta Czachowicz 2023.

a terrace. During the owner's absence, the glass walls are secured with gates spanning the entire height of the building, which adapt to the user's needs. Furthermore, the external finish can be altered according to local regulations and aesthetic preferences.

From an economic standpoint, it is crucial to utilise appropriate construction materials, such as wood instead of plastics, and windows with superior thermal performance. The high-quality wooden planks employed in the construction of the terrace in Podgać exemplify an aesthetic appeal that is also characterised by durability. The modular construction method allows for the rapid erection of buildings, while the use of high-quality materials ensures cost-effectiveness. The incorporation of renewable energy sources, such as photovoltaic panels, reduces the associated costs of electricity. The compact dimensions of Dom Baby Jagi result in reduced construction and maintenance costs.

The rising costs of energy have prompted developers to seek ways to reduce their expenditure by installing devices powered by renewable energy sources or constructing energy-efficient homes. The examined building is a simple, compact rectangle, which reduces operating costs. The entrance is located at the front, and the wooden window provides natural lighting to the living room and loft. Wooden gates protect the entrance and insulate against the cold. The gabled roof minimises heat loss and costs. Wooden houses are well-insulated, reducing operational costs. The adaptation includes the optimal utilisation of photovoltaic panels and sunlight, which provides more daylight during the day and better insulation at night.

From an ecological perspective, the discussed building exemplifies the principles of sustainable construction. During both the design and construction phases, environmentally conscious materials were utilised, and meticulous attention was paid to ensure a healthy indoor microclimate and enhance the productivity of residents (JWA, 2023). Another noteworthy aspect of the project in Podgać is the incorporation of a rainwater tank. This solution allows for a reduction in the use of tap water, with additional benefits including the softness of water, low chlorine levels, and high nutrient content in rainwater compared to tap water (Rolmarket.pl, 2019). The property also benefits from its location in the heart of the forest, which results in lower temperatures during the summer by several degrees compared to urban areas, while in winter, some of the flora shields the building from the wind. Trees not only provide shade but also, by their nature, allow for breathing in clean air. The use of photovoltaic panels makes the facility not only economical and energy-efficient but also ecological. By reducing electricity consumption from the grid, which is generated primarily from coal combustion in Poland, the facility is contributing to the reduction of greenhouse gases. Figure 4 illustrates the structure of electricity production in Poland.

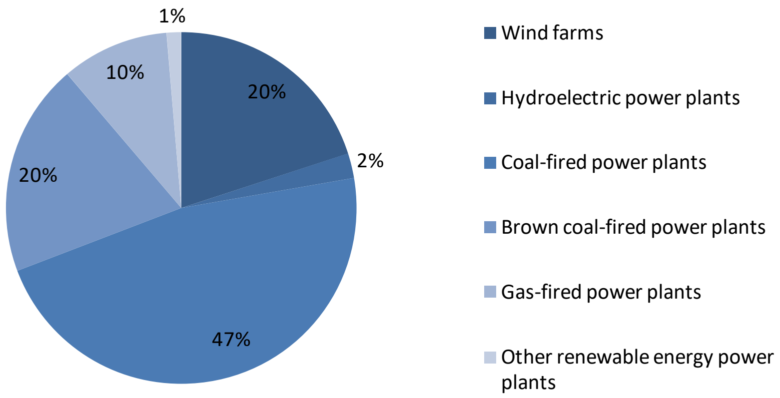

Fig. 4. Structure of electricity production in Poland in December 2023

Source: own work.

The recreational cottage, designated as Dom Baby Jagi, is a simple, ergonomic rectangular structure. It comprises a living room, kitchen, dining area, bathroom, and a loft bedroom that overlooks the forest. Its straightforward design enables various configurations and year-round utilisation, thanks to its wooden construction with insulation. There are three variants (models A, B, C) available, which can be modified to align with the developer's preferences and site conditions. The utilisation of prefabricated modular elements enables the circumvention of the 'construction season' and the reduction of costs.

Modern construction is characterised by simplicity, ecology, and the efficient use of materials and space. The examined building exemplifies these characteristics, integrating aesthetics, solidity, and functionality. Designers and developers endeavoured to adapt the project to the surroundings by choosing a simple form and a wooden façade, which allows the building to harmoniously blend into the landscape. Efforts were made to minimise tree cutting and comply with the provisions of the building conditions decision, which is crucial for the development area. The absence of artificial pavements and the use of natural materials such as wood further enhance the aesthetic appeal of the surroundings. Such harmony with nature positively affects the well-being of the residents, creating an atmosphere of tranquillity and harmony.

The discussed small house has been optimally utilised, accommodating a living room with a kitchenette, a bathroom, and a bedroom on the mezzanine. Despite its small size, each room has all the necessary elements. The compact bathroom (2.3 m^2) limits space for residents, although it features a shower instead of a bathtub to save space. The mezzanine has been incorporated in an unconventional way for small buildings, although the stairs leading to the bedroom are narrow and steep, replacing a ladder. The living room with a kitchen is the largest room (23.6 m^2), allowing free movement without corridors, and ergonomically designed walls have recesses for cabinets. The roof enables the installation of photovoltaic panels or solar collectors, saving space on the plot and utilising ecological solutions.

The principle of reduction is applicable to various elements and aspects of the construction process, commencing with the planning of the building on the plot, continuing through its construction, and concluding with its use. The reduction of waste in this project commenced during the design phase. Due to the attractiveness and aesthetic qualities of the plot, it was determined that the project would be of a modest size but would possess all the necessary features of a year-round home. Proper quantification allows for waste reduction, its proper management, and planning of necessary materials, deliveries, and construction equipment. An important aspect is also adapting the technology, location, and shape of the building to the site. In the discussed example, the building was designed in such a way that photovoltaic panels could be installed on the roof, or a heat pump could be used. Additionally, the house was rotated to the east by 18° to optimise the sunlight exposure of the roof and façade. This action helps to reduce heat loss and to maximise the use of panels on the roof. The technology used to construct the house in Podgać is relatively fast to implement. The building was not constructed on-site; ready-made elements made of prefabricated wooden technology, which minimises waste and enables their proper management due to their further processing at the factory, were transported to the construction site and then assembled into the complete structure. This solution also features a quicker implementation time than traditional construction. Moreover, during the construction process, the construction team utilised energy-efficient equipment, and any unused materials were returned to the store for reuse in another construction project. In the operational phase of the facility, devices and household appliances were also selected for their energy efficiency.

The term reuse refers to the reuse of materials, and in the context of the discussed topic, it signifies the conscious utilisation of equipment and building materials, thereby saving natural resources. The technology of wooden houses is environmentally friendly because, after tree felling for construction purposes, new plantings are carried out. This practice ensures that the number of forests does not decrease and provides new material for the future. Furthermore, the process of growing trees does not require energy, and the plants themselves absorb large amounts of carbon dioxide. In the construction of the building, concrete technology was employed solely for the purpose of erecting the foundation footings, which were constructed using reusable formwork that will be utilised for future projects. The remainder of the structure is based on a wooden frame. Another significant factor for developers was the utilisation of restored old furniture that was destined for disposal, as well as the aforementioned rainwater tank.

The final principle of the 3Rs is recycling. The structure of the Dom Baby Jagi can be dismantled with relative ease. Once this procedure is complete, the area can be restored to its original state with minimal delay. The wooden materials that comprise the structure can be reused, and any surplus can be used as fuel. During the process of tree growth, stored carbon dioxide is released again, closing the carbon dioxide cycle. Furthermore, in the event of a potential relocation, individual elements are disconnected, transported to a new location with the prepared ground, and finally, the wooden structure is reassembled. The use of wooden prefabricated elements has resulted in the collection of any wood waste at the sawmill, where it undergoes further processing and is used for other purposes.

Half-timbered building in Jarzębia Łąka

Another example of an ecological building is a house constructed from clay-straw bricks. The house in question was constructed using an economic system (Fig. 5). The clear advantages of the property are its ecological and health-related aspects. The house aesthetically blends in with the surrounding pine forest. It is a standalone building without a basement. The main building materials are wood, clay, and rye straw. The final material, rye straw, must be of good quality, precisely threshed, and weed-free. Otherwise, grains and other seeds could sprout. The straw used during construction was seasoned and consists only of woody stems, providing better protection against rot. An essential factor during construction was the proper scheduling of construction and assembly work, just like in the case of the Dom Baby Jagi. The house was erected on concrete foundations, and then the wooden frame was assembled. In the final stage of construction, the roof is covered to protect the walls from rainwater. The empty spaces between the wooden frame were filled with clay-straw bricks, taking into account fire safety concerns. Subsequent stages of construction were similar to standard builds, involving the construction of partition walls, plastering, façade work, carpentry, long-term roof covering, and installation distribution.

The building was constructed on a less expensive rural property but has good railway connections to Warsaw. Furthermore, construction materials were used that maintain their properties over a longer period of use. In the described half-timbered building, bricks made of weed-free and mould-resistant straw, as well as clay treated with antifungal agents, were used. Additionally, the straw in the bricks was arranged to achieve the best insulation. The lowest heat transfer coefficient observed during testing was 0.073 $W \cdot mK^{-1}$ for a wall thickness of 40–45 cm (Podwysocka, 2017). The use of straw from an economic system resulted in a notable reduction in construction costs for the building. The analysed building was designed to be easily constructed and to have an interior design that utilised a gabled roof and a simple, functional gable shape (Malińska, 2022). These factors indicate a reduction in costs from the design stage through construction to operation.

One of the key advantages of the project in question is the reduction in operating costs, which can be attributed to the simplicity of the building's structure and its location on the plot. The roof, with a 30-degree slope, is insulated with 30-centimetre thick mineral wool. Furthermore, the building's orientation allows for the installation of photovoltaic panels on the southern-facing roof plane, which enables the maximum utilisation of the devices and, thus, their unparalleled electricity production. The electricity generated in this way will be used to heat the building and domestic hot water. Additionally, the applied technology has resulted in vapour-permeable walls (Podwysocka, 2017), without incurring additional costs. Furthermore, the house is located in the vicinity of forests. This is a measure that enhances not only the aesthetic and visual qualities but also the economic ones. The building is significantly protected from winds, thereby reducing the demand for electricity to heat the house.

Fig. 5. A view of the half-timbered building in Jarzębia Łąka, Poland

Source: photos by Aneta Czachowicz 2023.

One of the most crucial aspects of any construction technology is its environmental impact. This technology aligns with the principles of sustainable construction, as evidenced by its ability to create a healthy microclimate, construct buildings in a manner that respects the natural environment, and avoid the use of chemical compounds that may cause allergies (Podwysocka, 2017). Furthermore, in the case under study, natural agents were used for impregnation, namely building lime. This type of lime is recommended for more humid spaces because it possesses antifungal, antiseptic, and antibacterial properties (Balcerowska, 2020). It is also worth mentioning the previously cited heating system, which will utilise green photovoltaic energy, as well as the rainwater tank, from which water will be used for gardening purposes (Malińska, 2022).

The single-family residential building is a detached, single-storey structure with a partially usable attic and no basement. It comprises one bedroom, a living room with a kitchenette, a bathroom, a utility room, and a study. The half-timbered house is distinguished by its functional structure and rectangular shape. The simplicity of its design allows for a wide range of design possibilities. The flexibility of the examined construction is evident in the variety of finishing options available. The developer selected the most environmentally friendly solution, which involved the use of external and internal plaster made of clay, whitened with natural lime. However, this was not the only option available, as there was also the possibility of using natural cladding boards for the façade.

The principles of the 6Es encompass not only functional and environmentally friendly considerations but also aesthetic concerns. In the case under study, the plot for construction was carefully selected to create a healthy microclimate with the surrounding nature and to minimise the impact of the development on the environment. The building was designed to preserve the bordering trees and to provide views of the forest from the windows. The plot is located at the last line of development before the forest. The building's distinctive appearance is derived from the use of natural and minimally processed materials, including wood, straw, and clay, in its construction. These materials contribute to the building's visual distinction from the ubiquitous concrete structures that are prevalent in urban areas. The simplicity of the colour scheme and technology employed in the design of half-timbered houses, which originated in rural Poland, is evident in the building's design. The integration of the building into its surrounding environment, evoking images that many people may recall from their childhood, is another factor that contributes to the building's aesthetic appeal. The strategic placement of windows not only allows for the illumination of rooms but also enables the observation of picturesque views. These features contribute to the building's seamless integration with its natural surroundings. The project demonstrates that eco-friendly construction is not incompatible with modernity or functionality and can be aesthetically pleasing at the same time.

The selection of the described half-timbered house technology in wooden construction with the infilling of clay-straw blocks is in accordance with the principle of ergonomics. The building combines the comfort of use in a space made from natural materials. Surrounding the building is nature in the form of forests and meadows. Due to its simple construction and the limited number of internal walls, there is greater flexibility in adapting the rooms to the user's needs and comfort. The building contains all the necessary facilities and rooms for human habitation. It is usable year-round, providing coolness in the summer and effectively retaining warmth in the winter. In addition to the previously mentioned solar panels installed on the roof, an ecological cesspool was also constructed, which, besides its benefits to nature, facilitates the use of the property by reducing the frequency of tank emptying. The building's convenient two-flight, broken stairs with a landing connect the ground floor with the attic, enhancing internal accessibility. Its construction and execution methods are unconventional in comparison to modern standards, but just a few hundred years ago, they were popular and widely used. The building was primarily created as a place to live and spend leisure time surrounded by nature.

Ecological construction is closely related to reducing the generation of waste during construction, minimising resource wastage, and opting for environmentally friendly products in biodegradable packaging. It is important to note that, like any other construction project, waste is generated during the building process, but this is mostly organic waste. The majority of these leftovers can be collected as compost, including wood scraps, straw shavings, or clay residues. Proper insulation of the roof and foundations, as well as the use of wide walls with a high heat transfer coefficient for partitions, allows for a reduction in heat production, thus lowering the costs of electricity. Another reduction can be seen in the shape of the building. The half-timbered house was erected on a rectangular plan, allowing for cost reduction in both the design and construction stages. The same aspect applies to the simple, gable roof structure. The construction phase itself also mitigated many problematic effects of the chosen technology. Due to the use of clay-straw blocks, which require a period of drying before use and cannot be exposed to moisture, the house was constructed during the warmest months of summer, eliminating the need for energy-consuming heaters.

The concept of reuse is associated with consumer awareness of the reuse of products designated for disposal. One example of this is the decision of a developer to use wooden pallets as interior decor elements in the house, such as a coffee table or garden furniture. Another characteristic feature of the half-timbered house is the absence of rubble and a reduction in the amount of construction waste by utilising materials that are not transported in disposable packaging, such as packaging films, compared to traditional construction technology. A number of ecological technical infrastructure devices were installed on the property. The absence of a sanitary sewer collector necessitated the construction of an environmentally friendly domestic sewage treatment plant. Furthermore, in order to reduce water consumption and save water on the property, two retention tanks were constructed to collect rainwater. The water collected in this way is used for gardening purposes.

The recycling of materials is a fundamental aspect of the economic cycle in the construction sector. During the design and erection of a building, it is crucial to select simple materials with a low carbon footprint that are relatively straightforward to reintroduce into the cycle, such as wood. The aforementioned example represents an exemplary case of architectural recycling. It was constructed from natural building materials with minimal processing, which facilitates eventual dismantling and enables the majority of materials to be reused for construction or other purposes. The pursuit of recovering and reusing the majority of building materials from previous projects is a crucial aspect of ecological construction (Bukowski & Fabrycka, 2019). The construction of any building is inherently associated with environmental degradation, yet the less degradation, the more ecological the endeavour. The analysed building performs exceptionally well in this regard, thanks to the use of natural and biodegradable materials. Moreover, the construction site was equipped with an appropriate compost bin for the storage of natural waste, thus ensuring the maintenance of cleanliness.

Our heritage encompasses the natural environment, and its future appearance depends on the actions of present and future generations (Assmann, 2018; Bihari, 2023). Society faces numerous environmental challenges, including climate change, waste management, and soil, water, and air pollution (Koop & van Leeuwen, 2017; Yang et al., 2023). To overcome these difficulties and address the increasingly growing shortages of housing resources, pro-environmental and health-promoting principles and sustainable development practices are being introduced. The field of construction has a profound and far-reaching impact on the natural environment (Kietliński, 2015). Consequently, it is imperative to integrate architecture with environmentally conscious solutions (Vaverková et al., 2023).

The changes in living conditions in the 20th century highlight the necessity of considering the environment, with particular emphasis on the rapid decline of fauna and flora (Kietliński, 2015). In the contemporary era, we have more opportunities and access to environmentally friendly technological solutions, which facilitate the implementation of eco-friendly solutions in the construction industry (Zhang & Tu, 2021; Owen, Murtagh & Simpson, 2023). The foundation of this approach lies in the prioritisation of eco-friendly solutions that utilise natural materials which have been minimally processed or recycled (Chang, Long, Zhou & Ma, 2020; Zhang & Tu, 2021). The introduction of earth construction technologies represents a significant step towards sustainable construction (Hall, 2020; Morel et al., 2021). This is a response to the need to reduce the negative impact of human activity on the natural environment. Moreover, in the context of dynamic technological advancement, the availability and advancement of new solutions enable the even more effective and efficient use of earth as a building material.

The technology of building houses with earth is an environmentally friendly solution (Hall, 2020; Islam, Elahi, Shahriar & Mumtaz, 2020; Morel et al., 2021). The method utilises natural materials, typically local ones. Earth is a highly versatile building material. According to the International Centre for the Research and Application of Earth Construction (CRAterre), there are many possibilities for using soil in construction. Shaped earth, earthbags, or earth coverings are just a few examples of soil application in construction. One example of a building constructed using shaped earth is the buildings in Cameroon (Wati, Bidoung, Damfeu & Meukam, 2020; Ganou Koungang et al., 2023; Fig. 6).

The technology of shaped earth involves the direct shaping of moist, pliable soil, typically using hands or traditional, non-mechanised tools. Buildings constructed from rammed earth are shaped similarly to pottery. Shaped earth technology allows for the creation of intriguing architectural forms that do not require additional supporting structures. Controlling shrinkage caused by drying is a key issue, as it is in most other technologies of building with pliable earth. It is notable that shaped earth technology is still employed in numerous countries across Africa (Narloch, 2017).

The utilisation of earthbag technology is a common practice in Oman (Bizzarri et al., 2020). One example of such a building is a residential house constructed with earth-filled bags covered with clay plaster in Shuwaymiyah, Dhofar Governorate, Oman (Fig. 7).

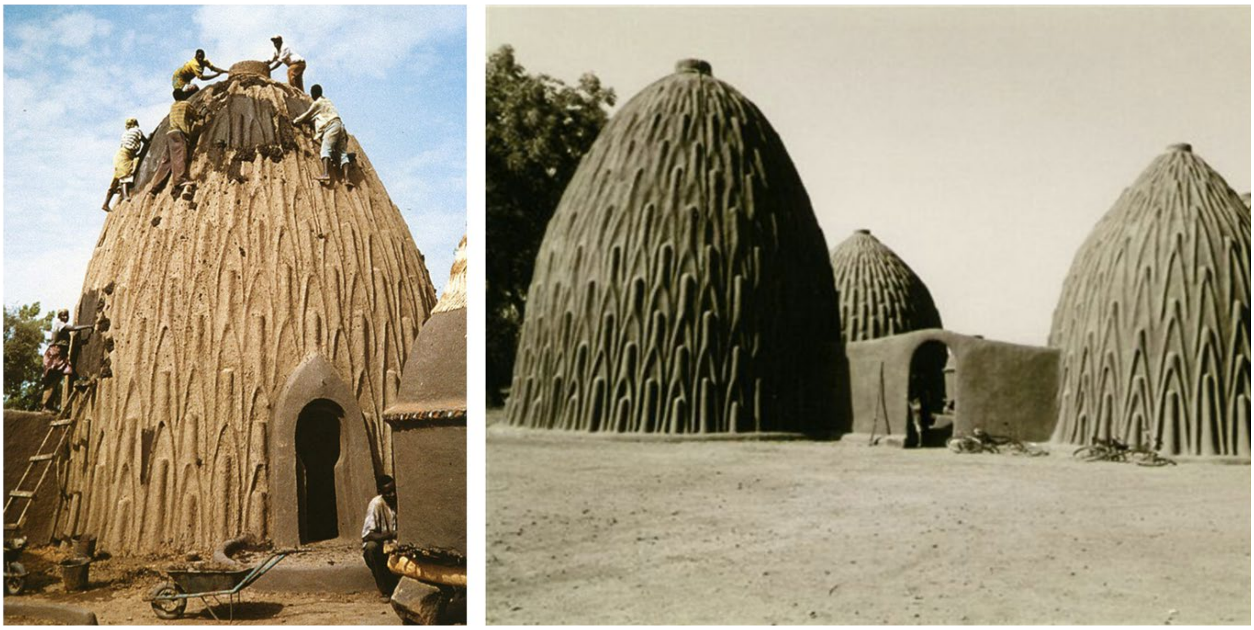

Fig. 6. Shaped earth buildings, Cameroon

Source: Chin (2010).

Fig. 7. House made of bags filled with earth and finished with clay plaster, Oman

Source: SSH (2024).

According to Narloch, this technology involves the filling of building elements with soil made from other materials. One type of this technology is the method of soil-filled bags. Plastic bags serve as a type of disposable formwork. Filled bags are stacked without mortar, and the structure is load-bearing due to the interaction of the core with the soil and the bag's shell (Narloch, 2017).

Figure 8 shows a residential building with a green roof in the Polish shopping centre, Galeria Sfera. The roof is covered with a layer of soil and vegetation, creating a lush and green landscape atop the building. This eco-friendly roofing solution not only enhances the aesthetic appeal of the home, but also provides numerous environmental benefits, including improved insulation, reduction of the urban heat island effect, and mitigation of stormwater runoff. The image illustrates how sustainable building practices, such as green roofs, can be integrated into residential architecture to promote biodiversity, energy efficiency, and overall environmental sustainability (Berg, Adamcová, Barroso, Šourková & Vaverková, 2020; Berg, Hurajová, Černý & Winkler, 2022).

Fig. 8. Residential house with a green roof covered with earth and vegetation, Galeria Sfera, Poland

Source: photos by Magdalena D. Vaverková 2023.

The technique of earth sheltering, also known as green roofing, involves the covering of external building walls, primarily roofs, with a layer of soil. It is a type of green roof where soil is used for insulation and roof covering, reducing the environmental impact of the building and improving energy efficiency. Additionally, it can serve as a way to utilise rooftop space for plant cultivation or gardening. As a result, buildings can be more integrated with nature and more energy-efficient.

Wood is the second most popular natural material, as observed by Sotayo et al. (2020) and Vaverková et al. (2023). In industry literature, it has been noted that green construction is becoming an increasingly common solution for developers, especially in the construction of single-family homes. Wooden houses are particularly popular due to the natural characteristics of wood as a building material. However, it is essential to select appropriate materials and technologies to ensure that the house meets the criteria of sustainable construction (Bielenis & Swalski, 2021). In order to enhance the durability, reduce the susceptibility to cracking during drying, and enhance the resistance to insects and fungi, it is recommended that wood be harvested during the winter season and during the waning phase of the Moon (Kownacki & Błaszczyński, 2019).

The construction of pagodas (ancient temples in Japan) was historically dependent upon the use of wood obtained during the waning phase of the moon. If properly prepared, wood has the capacity to withstand thousands of years, as it has endured numerous earthquakes and challenging conditions (Kownacki & Błaszczyński, 2019). Currently, moon wood is also being utilised (Fig. 9).

Fig. 9. Hōryū-ji Temple, Japan[a] and Hotel Mayr, Italy[b]

Source: [a]photos by Magdalena D. Vaverková by 2023; [b]Thoma Holz100 Canada (2024a, 2024b).

Passive houses (Fig. 10) are highly energy-efficient in operation, eliminating the need for a typical heating system (Schnieders et al., 2020; Mushtaha et al., 2021). Instead, they utilise minimal energy for heating, primarily through solar energy and heat generated by occupants and electrical appliances. In instances where supplementary heating is necessary, these structures rely on renewable energy sources such as heat pumps or biomass, which may only be required on days with exceptionally low temperatures. Due to their excellent thermal insulation, these houses consume a minimal amount of heating energy, typically around 15 $kWh \cdot m^{-2} \cdot year^{-1}$), which is comparable to the energy consumption of a small amount of gas, wood, or coal (Kaliszak, 2019).

Wooden skyscrapers are tall buildings constructed primarily from Wood (Almusaed & Almssad, 2022; Niiler, 2022). They are designed to ensure adequate strength and stability of the structure using advanced wood technologies, including glued laminated timber, engineered wood, and cross-laminated timber – CLT (Stach, 2020; Tulonen, Karjalainen & Ilgin, 2020). Figure 11 depicts a wooden skyscraper in Norway.

The buildings discussed in this paper demonstrate that the synergy between construction, sustainable development, and environmental stewardship is achievable (Scharlemann et al., 2020; Vaverková et al., 2023).

Fig. 10. Passive wooden house by Juri Troy Architects, Austria

Source: Quah (2013).

Fig. 11. Mjøstårnet wooden skyscraper, Norway

Source: Polskie Domy Drewniane SA (2020).

While sustainable building practices offer promising solutions for mitigating environmental impacts, it is critical to critically assess the challenges and limitations associated with their implementation. A key challenge is the availability and cost-effectiveness of green materials and technologies (Mariotti et al., 2020; Samadi et al., 2020; Alqahtani, Abotaleb & ElMenshawy, 2021). For example, while wood is a renewable resource, its extraction and processing can still have an environmental impact if not managed sustainably (Akpan, Wetzel & Friedrich, 2021; Schubert, Panzarasa & Burgert, 2022). In addition, the transportation of materials to construction sites can result in carbon emissions, especially if they are sourced from distant locations (Vaverková et al., 2023). The adoption of building technologies utilising earth can also face regulatory and cultural barriers, as building codes and practices often favour conventional materials and methods. In addition, while passive houses and timber skyscrapers offer energy-efficient alternatives, their initial cost and potential long-term maintenance requirements may deter widespread adoption, particularly in regions where traditional construction methods are entrenched (Hasper et al., 2020; Yang, Cho, Yun, Hong & Kim, 2021; Welch, Obonyo & Memari, 2023). In addition, the scalability of these practices to meet the growing demand for housing, especially in urban areas, remains a challenge. Overcoming these barriers will require a collaborative effort among policymakers, industry stakeholders, and communities to incentivise sustainable building practices, invest in research and development, and revise existing regulations to support the transition to greener building practices. By recognising and addressing these challenges, the building sector can move closer to realising its potential as a driver of positive environmental change.

CONCLUSIONS

In the contemporary era, construction professionals must integrate building technology with an awareness of the need to maintain harmony with nature. It is essential that basic human needs are met in a conscious manner, and that modern construction does not disrupt natural processes or the surrounding environment. Environmental practices encompass not only the innovative transformation of wind, sunlight, or geothermal sources into electrical or thermal energy, but also a return to traditional building technologies. The use of natural building materials or proper building orientation are just two examples of classical building solutions that allow for the creation of a healthy and friendly microclimate for humans. The framework of modern construction is established by specific characteristics of eco-friendly buildings. The 6E concept and the 3R principle serve as the foundation for designing sustainable development practices. Whenever possible, natural and recycled materials should be used. By adapting an old structure to a new one, material consumption can be reduced, resulting in a decreased financial investment required for building construction. Modularity, variability, and flexibility of functions, as well as the possibility of frequent adaptation to the environment, should be characteristic features of intelligent buildings. Such solutions will undoubtedly support nature and its resources. By implementing sustainable development practices, people will strike a balance between consumerism and economic and ecological optimisation.

In response to a series of doubts regarding ecological construction, specific principles have been developed to describe this scope of knowledge. Given the current environmental situation and the continuous demand for construction, there is a need for pro-environmental actions at the individual, social, and institutional levels. The most significant characteristics of ecological construction are the 6E concept: economic, energy-efficient, ecological, elastic, aesthetic, and ergonomic, in addition to the 3R principle of reduce, reuse, and recycle. The buildings described in the article met the criteria of 3R and 6E. In the context of ecological construction, this encompasses not only contemporary solutions and technologies but also a return to traditional construction methods. The examples of wooden buildings and timber-framed houses serve to substantiate this thesis and demonstrate that it is possible to combine modernity, ecology, and tradition in construction.

Authors' contributions

Conceptualisation: A.C. and M.D.V.; methodology: A.C.; validation: K.K. and M.K.; formal analysis: A.C.; K.K. and M.K.; investigation: A.CZ.; data curation: A.C.; K.K. and M.K.; writing – original draft preparation: A.C.; K.K. and M.K.; writing – review and editing: M.D.V.; visualisation: A.C.; K.K. and M.K.; supervision: M.D.V.

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

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BUDOWNICTWO PRZYJAZNE ŚRODOWISKU WRAZ Z PRZYKŁADAMI ZREALIZOWANYCH ROZWIĄZAŃ

STRESZCZENIE

W obliczu obecnych wyzwań środowiskowych, przed którymi stoi ludzkość, konieczne jest podjęcie działań proekologicznych, korzystnych dla zdrowia oraz praktyk zrównoważonego rozwoju. Istotne jest globalne wdrażanie ochrony środowiska, mając na uwadze niepokojącą przyszłość oraz długofalowe konsekwencje dla kolejnych pokoleń. Zielone rozwiązania budowlane są wdrażane na całym świecie, ale nie zawsze w odpowiedni sposób. Każda zielona architektura powinna integrować zrównoważony rozwój i ochronę środowiska przyrodniczego, niezależnie od lokalizacji. Niniejszy artykuł podsumowuje i charakteryzuje koncepcję ekologicznego budownictwa 6E (ekonomicznego, energooszczędnego, ekologicznego, elastycznego, estetycznego, ergonomicznego) oraz zasadę 3R (redukcja, ponowne wykorzystanie i recykling). W artykule przedstawiono również analizę dwóch ekologicznych budynków w Polsce. Pierwszym z nich jest drewniany budynek zlokalizowany we wsi Podgać, który stanowi przykład połączenia nowoczesnego designu i dbałości o minimalizowanie negatywnego wpływu na środowisko przyrodnicze. Został on zbudowany w zgodzie z naturą i wkomponowano go w naturalne środowisko lasu. Dom we wsi Jarzębia Łąka to drugi przykład łączenia tradycyjnego budownictwa, nowoczesnych rozwiązań technicznych z ochroną środowiska przyrodniczego. Przedstawione przykłady inwestycji zostały przeanalizowane pod kątem zasad budownictwa ekologicznego, a następnie porównane z koncepcją 6E i zasadą 3R. W artykule przedstawiono kompleksowe badanie dwóch różnych ekologicznych konstrukcji budowlanych. Badanie to obejmuje charakterystykę techniczną, zgodność z koncepcją 6E, porównanie efektywności ekologicznej oraz wnioski z zaleceniami. Dom Baby Jagi we wsi Podgać jest przykładem harmonijnego połączenia prostoty, funkcjonalności i oszczędności z wykorzystaniem drewna z izolacją w celu przystosowania budynku do całorocznego użytkowania. W obiekcie zastosowano technologie odnawialnych źródeł energii i system zbierania wody deszczowej, co przyczynia się do zrównoważonego rozwoju ekologicznego. Tymczasem do budowy obiektu z muru pruskiego w Jarzębiej Łące wykorzystano cegłę z gliny i słomę, co zwiększyło korzyści ekonomiczne i środowiskowe, które uzyskano także dzięki zastosowaniu w projekcie paroprzepuszczalnych ścian i wydajnej izolacji. Obie konstrukcje stanowią przykład ergonomicznego projektu, ekologicznych praktyk budowlanych i estetycznej integracji z naturalnym otoczeniem. Analiza studium przykładów unaocznia znaczenie włączania rozwiązań przyjaznych dla środowiska przyrodniczego do nowoczesnej architektury w celu stawienia czoła współczesnym wyzwaniom środowiskowym i promowania zrównoważonego rozwoju.

Słowa kluczowe: budownictwo przyjazne środowisku, praktyki zrównoważonego rozwoju, zielone rozwiązania budowlane, koncepcja 6E, zasada 3R