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Research paper

Key determinants of autonomous building development

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Abstract: The construction and operation of buildings is characterized by resource intensity in the form of massive consumption of raw materials and products, large financial and human labor expenditures, energy consumption, water consumption, long term, and significant environmental impacts, especially during their use. The currently implemented concept of sustainable development and circular economy influences the directions of development of construction industry and increases interest in self-sufficient buildings, especially in terms of energy, use of closed water circuits, use of waste materials. The aim of the article is to analyse the key determinants for the development of autonomous buildings. The general idea is that an autonomous building is designed to function without the support and services provided by public facilities, such as power, water, gas and sewage networks, waste management, and even the provision of food. On the basis of literature analysis and expert interviews, the factors characterizing this type of construction were determined. Their analysis by means of the DEMATEL method allowed to assess and indicate the most significant cause-and effect relationships conditioning the development of autonomous buildings.

Keywords: autonomous buildings, DEMATEL method, earthships, operation of building

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1. Introduction

The demand for residential buildings is constantly growing. In Poland, the number of new residential buildings commissioned in 2021 increased by 17.8% compared to 2020. Single-family buildings accounted for 97.3% of all buildings commissioned [1]. In 2019 46.1% of the EU population lived in apartments, more than a third (34.8%) in detached houses, and almost a fifth (18.5%) in semi-detached or terraced houses [2]. Poland is one of the few EU member states where the proportion of detached houses residents is still the highest, which is due to suburbanization and lower prices of building plots than in the city with simultaneous access to well-developed communication infrastructure [3, 4].

The perception of the building sector as one of the principal areas of human activity makes it very important in the context of sustainable development to increase energy efficiency and even to move towards energy autonomy of the building, hence the development of buildings even "zero energy" [5]. The pursuit of economy and autonomy includes the supply and consumption of water for the needs of the residents (closed circuits), reducing the discharge of wastewater into the municipal sewage system and storm water. These measures help protect the environment and reduce life cycle maintenance costs [6, 7]. The need to protect natural resources and economize in production and use develops circular economy, forces to economize in the consumption of raw materials and products, develops recycling and waste management. In terms of social needs, there is an increase in the requirements for comfortable living, working conditions, which increases productivity and provides better living conditions (clean air) and safety.

As research shows, an initial investment of $2 \div 10\%$ in the design, can help save about 20% of the total operating costs during the life cycle of the building [8]. The continuous increase in the prices of both the construction and operation of buildings directs investors to choose materials and solutions both affordable and characterized by later consequences in the form of reduction of the operating costs of objects.

The above-mentioned aspects make the residential construction still developing. Significant technological, economic, and social problems are still emerging, resulting in the emergence of new technologies and forms of construction. Continuous problem solving and development also contribute to progressive changes in other spheres of public life, in particular to the formation of more comfortable living conditions for the population, the increase of their welfare and care for the environment [9]. With the current natural disasters, geopolitical situation and threat of armed conflict, there seems to be a growing need and interest for autonomous buildings. This concept is also particularly relevant for buildings located in places with difficult access to infrastructure [10].

The aim of the paper is to analyze the determinants of the development of autonomous buildings. The publication contains a literature review on the development of the concept of autonomous buildings and the analysis and evaluation of the cause-and effect relationships of the factors determining the development of this type of buildings using the DEMATEL method on the example of "earthships".

2. Development of autonomous buildings

Taking into account aspects such as social conditions, implementation of sustainable development and circular economy, financial, technological, legal, and political aspects, several concepts of residential construction development can be distinguished. Since the energy crisis in the 1960s, research and initiatives have been initiated to improve energy efficiency and reduce environmental pollution [11]. For many years, the goal has been to reduce energy and water consumption, waste production, and environmentally friendly and health-oriented solutions [8, 12]. The need for renewable energy sources, photovoltaic technology, the use of trees and plants to create green roofs and rain gardens [8]. Additionally, the construction sector is moving from a linear economy model to a circular economy model, which aims to reduce the use of new resources and encourage the use of recycled materials [13]. The drivers of these modifications include EU legislation and policy [7]. Prominent among them are decisions such as the policy framework for climate and energy [14], the Energy Roadmap [15], the roadmap for moving to a competitive low carbon economy [16], and the list of energy efficiency improvement projects [17]. As a result of these actions, year after year the requirements for the heat transfer coefficient were made more stringent (for 2022 it is 0.20 $W/(m^2 \cdot K)$ – for walls and 0.15 $W/(m^2 \cdot K)$ – for roofs) [18, 19]. an energy performance certificate was introduced for some buildings, as well as the possibility of obtaining financial support for the purchase of equipment enabling the use of renewable energy sources. Other programs are also emerging, such as Advancing Net Zero, a global project of the World Green Building Council to support efforts to decarbonize the building sector by 2050 [20, 21]. Growing pressure for high energy efficiency in buildings has made the production of thermal insulation materials one of the most dynamically developing areas of the building materials market [18]. Some are designed not only to reduce heat flow through the building envelope, but also to capture, store and return external energy to the building [18]. Attention is also paid to the use of environmentally friendly, natural, and recyclable materials. To facilitate verification, environmental declarations have been introduced for construction products, e.g., EPDs, which contain information on the environmental impact of the declared product during its life cycle [22]. The “sustainability” rating of a facility is determined using building rating systems – certification [23]. The most important and popular are the American – LEED and the British – BREEAM. In recent years, the following types of sustainable buildings can be distinguished (often interrelated): **autonomous (otherwise self-sufficient)**, smart [24, 25], passive, energy efficient, low-energy, plus energy, Net-Zero Energy Building (NZEB), green buildings [26].

The general idea is that an autonomous building is designed to function without the support and services provided by public facilities, such as power, water, gas and sewage networks, waste management, and even the provision of food [27]. In the work [28], building autonomy is defined as the ability of a building, over its long lifetime, to function without negative impact on the external environment. However, autonomy often refers only to energy. As early as the 1970s, buildings were designed along the lines of autonomous buildings – "bioshelter", which used wind to pump water and generate electricity and were autonomous in terms of food production. The facilities had living quarters, fish tanks, greenhouses irrigated with water from a tank, and a closed loop sewage reclamation system that turned waste into fertilizer [29]. The construction of an autonomous building is already possible today. All the necessary technologies exist. However, the problem remains cost [28]. It is possible to build a self-sufficient building for the same price as a conventional building, but 25% smaller [10]. Autonomous building design must be adapted to climate, topography, and location. Passive solar techniques, alternative toilets and sewage systems, efficient windows, and another design solutions require highly unusual construction, additional costs, and continual experimentation and refinement of the design [30].

Energy self-sufficiency is provided by the use of renewable energy sources (mainly solar) and supported by systems that enable energy storage. Heat pumps, photovoltaic installations and ventilation systems with heat recovery are used. Rising energy costs and favorable legal solutions result in a rapid increase in the number of such installations. The average drop in prices of photovoltaic modules alone in recent years has been about 10% per year [31]. However, it should be noted that achieving full energy independence is not yet common. This is due to the still high costs and the construction of installations that do not always cover the full daily energy demand (variability of conditions throughout the day and year) [28]. The paper [32] presents the alternative of using hydrogen energy for energy self-sufficiency. The use of zero emission technologies promotes the improvement of air quality, affecting the health and life of building occupants.

Closed water cycle is a well-known solution to use water efficiently and several times. It is still quite expensive. Desalination and rainwater collection are alternative harvesting techniques. They will become more common as water utilities seek new solutions by diversifying their approach to water supply [33]. In paper [34], a pilot study of a laundry wastewater recycling system was conducted. The system recovered 69% of the water used by the laundry while treating the wastewater to the required quality.

Solutions already exist that enable or bring a building closer to self-sufficient waste management. Most of them allow organic waste treatment – anaerobic digestion of food waste and composting. The exception is thermochemical waste treatment, especially low-temperature pyrolysis. Pyrolysis converts waste into fuel. After burning, the user obtains the final product – energy, which can be easily used, e.g., for heating water, and the by-products of the process do not pose a threat to human health and the environment [35].

Self-sufficient buildings meet many of the principles of green buildings (e.g., use renewable energy), but there is no guarantee that they are truly sustainable structures (autonomous does not always mean environmentally friendly). For this reason, the paper [10] recommend incorporating energy and life cycle cost analyses in the design of such buildings to avoid negative impacts and guarantee the sustainability of the facilities from an environmental and economic perspective. The publication [36] presents and compares methods of simple models to estimate the cost of building maintenance.

One of the examples of autonomous buildings are earthships. The principles on which the idea of earthship building is based are the use of local, recycled and waste materials in their construction (e.g., tires for walls), the use of renewable sources for energy production, the collection of rainwater and its use for living purposes and for watering plants enabling food production, during their operation i.e., use and maintenance. Buildings are in more than 40 countries and are located in all climate zones [37]. The paper [38] compares earthships located in different climate zones and concludes that Earthship buildings are least suited to tropical wet/dry settings. Figure 1 show example of earthship.

Fig. 1. Example of earthship in Taos New Mexico [39]

Earthships are being built in Poland, too. The first such facility has been built in the small town of Mierzeszyn near Gdansk. Actually, we are talking about several buildings, i.e., an outbuilding, a residential house and a facility for tourism and catering. The house has an area of about 150 m^2. The building is partially sunk into the ground which allows it to maintain a constant temperature in winter thanks to the soil's storage properties. The construction used 1,500 car tires obtained from local vulcanization plants, used cans, plastic bottles, recycled wood, and clay from the plot. The building is not connected to utilities. Electricity is obtained through photovoltaic panels and a wind turbine. Water is drawn from a well, and rainwater is also used. The owners also have their own sewage treatment plant. The building is reheated with a fireplace with a water jacket [40].

3. Cause-and-effect analysis of autonomous buildings development

3.1. Methods

For the purpose of achieving the objective of the study, the factors determining the development of self-sufficient building were extracted using the example of earthships. To develop them, a pilot questionnaire study conducted on the interest and public perception of these buildings and publications on similar research topics [37, 41] were used.

To investigate the identification of causal relationships in the issueunder consideration, the authorsused the DEMATEL method [42]. This method is widely used in the analysis of economic processes and in environmental aspects [43–45]. The DEMATEL analysis makes it possible to determine the cause-effect relationships between the elements of the system under consideration and the resulting role of individual components in the system.

For this purpose, it is necessary to determine the direct influence of individual components on the others in the considered system. The network of all links-interactions between elements is called the direct influence structure. On its basis, the structure of indirect influence (exerted through other elements of the system) is determined, and then the structure of total influence, including both direct influence and indirect influence of elements. The following calculation procedure was used:

I. To assess the relationships between factors, a direct influence matrix Z (Eq. (3.1)) was created to determine the presence of influence and its direction. The following impact scale was used in the analysis: 0 – no impact, 1 – small impact, 2 – significant impact.

$$Z = \left[z_{ij}\right]_{n\times n} \tag{3.1}$$

where: $i, j = 1, 2, \ldots, n$, $n \times n$ – matrix dimension.

II. In the next step, the determination of the normalized the grade values and direct influence matrix X (Eq. (3.2)) and Eq. (3.3)), and then the determination of the total influence matrix T (Eq. (3.4)).

$$X = \frac{Z}{s} \tag{3.2}$$

$$s = \max\left(\max_{1\le i\le n}\sum_{j=1}^{n} z_{ij},\ \max_{1\le i\le n}\sum_{i=1}^{n} z_{ij}\right) \tag{3.3}$$

$$T = X\,(I - X)^{-1} \tag{3.4}$$

where: s – scaling factor.

III. On the basis of the above matrices, the vectors R and C (Eq. (3.5)) were computed, as the sum of the rows and the sum of the columns from the total-influence matrix (t_{ij}).

$$R = [r_i]_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} \qquad C = [c_j]_{1\times n} = \left[\sum_{i=1}^{n} t_{ij}\right]^{T}_{1\times n} \tag{3.5}$$

Above vectors are the element of "prominence" ($R + C$), and "relation" ($C - R$), which successively illustrate the strength of the influences of the factor and effect that the factor contributes to the system [42].

The DEMATEL analysis included 26 factors that characterize and condition the development of autonomous construction classified as weaknesses and strengths, as well as surrounding opportunities and threats (Table 1).

Table 1. Factors considered in the analysis

Factor	Id*
Trend towards sustainable living;	**O1**
Increase education about autonomous building (including earthships);	**O2**
Development of wasteland;	**O3**
Demand for residential buildings;	**O4**
The desire to stop environmental degradation;	**O5**
Implementation of the sustainable development and circular economy strategy;	**S1**
Using recycled materials/locally sourced construction material;	**S2**
Integrating the building into the natural landscape;	**S3**
Easy to build ('do-it-yourself');	**S4**
Reducing building maintenance costs;	**S5**
Lower life cycle costs (LCC) compared to other buildings;	**S6**
Unusual/Unique lifestyle;	**S7**
Unsuitable technology for densely populated urban areas;	**W1**
Labour intensive building process;	**W2**
Need to adapt the design to the location;	**W3**
Utilities dependence on renewable resources and weather conditions;	**W4**
Initial costs greater than ordinary buildings;	**W5**
Futuristic/Unusual building;	**W6**
Difficulty in identifying suitable building plots;	**W7**
Use of waste materials/ not fully tested building materials;	**W8**
Weak recognition of safety and health aspects at the use stage;	**W9**
Difficulty in obtaining the necessary permits and permissions for planning/building;	**T1**
Difficulty in obtaining financing (high financial risk rating);	**T2**
Deficiency of qualified construction crews and designers;	**T3**
No legislation;	**T4**
Lack of technical specifications for autonomous building.	**T5**

* **O** – opportunities, **S** – strengths, **W** – weaknesses, **T** – threats.

3.2. Research findings and their analysis

Figure 2 presents the interrelationships/interactions of the different determinants of autonomous building development and their relevance, divided into strategic areas: weaknesses (W), opportunities (O), strengths (S) and threats (T).

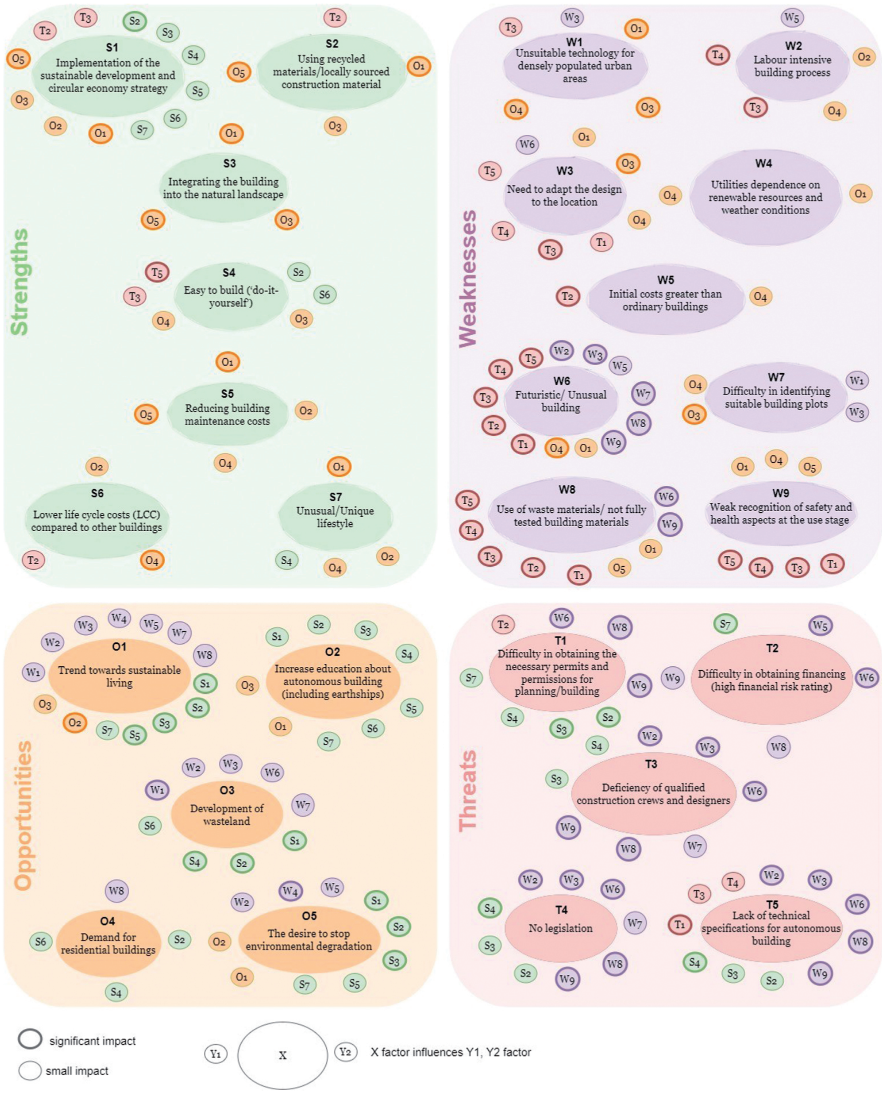

Fig. 2. Assessing the relationship between the determinants of autonomous building development

The strength (significance) of the impact was determined by the authors, based on the literature review that was conducted by A. Mach and summarized in the previous publication [43], as well as their own knowledge and observations. In a further computational process (Eq. (3.2)–(3.5)), the R and C vectors (Table 2) necessary to determine the strength of influence of the factors ($R + C$) as well as the effects that the factors bring to the system ($C - R$) were determined.

Figure 3 presents the obtained results of the analysis.

Table 2. Values of R and C vectors for individual factors

Id.	Factor	C	R
O1	Trend towards sustainable living;	1.81	1.61
O2	Increase education about autonomous building (including earthships);	0.75	0.70
O3	Development of wasteland;	1.11	1.14
O4	Demand for residential buildings;	0.33	1.23
O5	The desire to stop environmental degradation;	1.09	0.89
S1	Implementation of the sustainable development and circular economy strategy;	1.30	0.68
S2	Using recycled materials/locally sourced construction material;	0.62	1.39
S3	Integrating the building into the natural landscape;	0.64	1.04
S4	Easy to build (‘do-it-yourself’);	0.62	1.08
S5	Reducing building maintenance costs;	0.59	0.48
S6	Lower life cycle costs (LCC) compared to other buildings;	0.28	0.45
S7	Unusual/Unique lifestyle;	0.47	0.64
W1	Unsuitable technology for densely populated urban areas;	0.83	0.39
W2	Labour intensive building process;	0.66	1.02
W3	Need to adapt the design to the location;	1.09	1.25
W4	Utilities dependence on renewable resources and weather conditions;	0.19	0.29
W5	Initial costs greater than ordinary buildings;	0.22	0.68
W6	Futuristic/Unusual building;	2.09	1.58
W7	Difficulty in identifying suitable building plots;	0.49	0.62
W8	Use of waste materials/ not fully tested building materials;	1.78	1.19
W9	Weak recognition of safety and health aspects at the use stage;	0.99	1.17
T1	Difficulty in obtaining the necessary permits and permissions for planning/building;	1.32	1.08
T2	Difficulty in obtaining financing (high financial risk rating);	0.74	1.11
T3	Deficiency of qualified construction crews and designers;	1.27	1.42
T4	No legislation;	1.88	0.91
T5	Lack of technical specifications for autonomous building.	1.80	0.91

The analysis of relationship between factors shows that the main factor stimulating the development of autonomous buildings technology is the development of technical standards and adaptation of legal regulations to the atypical buildings (T4, T5). The observations are consistent with the results of studies [37], which indicate formal/legal barriers as one of the main threats to the development of such buildings. These studies suggest the need to

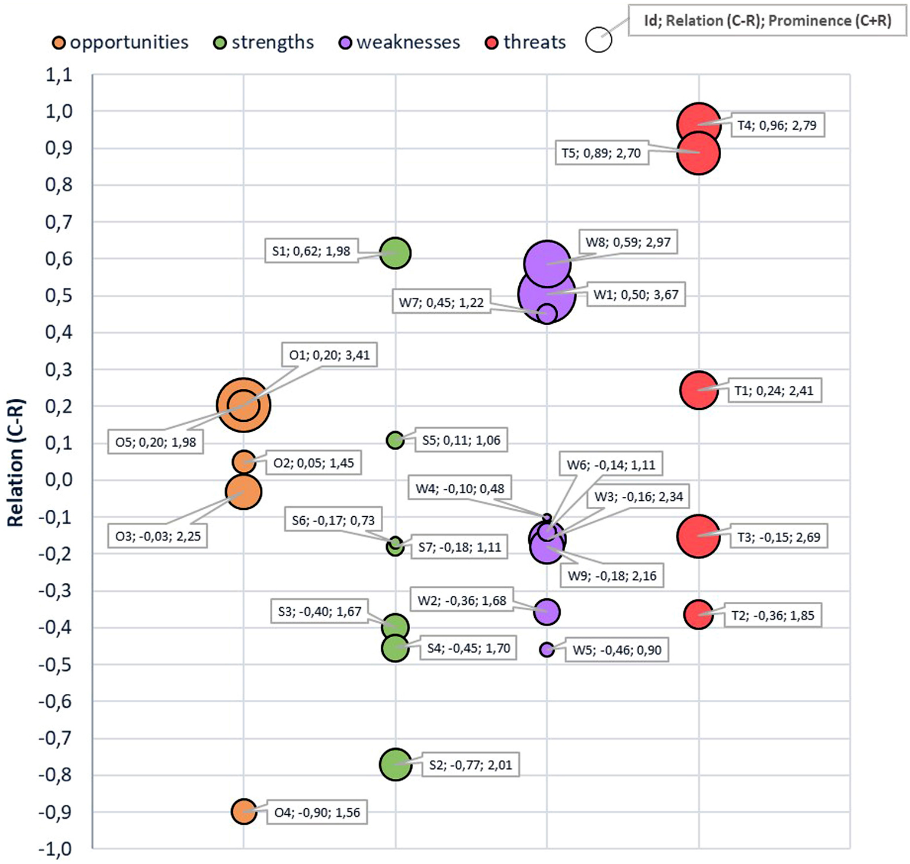

Fig. 3. Relation and prominence diagram

involve all participants in the construction process, in order to make a fluent transition from conventional to autonomous construction. The report [41] also indicates the significant role of availability of support and information from experts or institutions demonstrating knowledge of legislation and applied/possible technologies of autonomous buildings.

Unusual construction project (W6) brings many problems at the stage of realization and obtaining permits (T1, W1), it is worth to minimize in the design process the negative impact of this factor on the course of the construction process, costs, safety and health protection and limitations concerning the location of the building.

The idea of a circular economy assumes reuse of waste, but in the process of its recovery there are many legal, environmental, and technical difficulties. There is a need to develop a reasonable path for the loss of status of waste, which can be a safe building material (S1, W8).

The values of factor significance indices (weights) confirm that the weaknesses of the technology, such as unusual building design (W6) and the use of waste materials (W8), are the greatest barriers to technology development. The greatest opportunity for the development of technology is created by the visible growth of interest in ecological living (O1) and the implementation of the principles of the concept of sustainable development and circular economy (S1). The mentioned trend positively influences legislative changes and further development of technologies, which can minimize the weaknesses of technologies in the future. The participants of the already mentioned study [37] indicated environmental factors as outweighing operating cost savings. It is worth mentioning, however, that the group of respondents were people visiting the demonstration building. Despite the unrepresentative survey sample (it did not involve the general public), the results nevertheless indicate the increasing role played by environmental issues among potential investors.

4. Summary and conclusions

The concept of autonomous buildings is in line with current trends in residential construction development. The convergence includes decoupling from services provided by public facilities/organizations (critical for current geopolitical situation), as well as implementing the sustainable development and circular economy strategy. Despite the relatively new idea, many aspects still need to be improved both in terms of costs (as emphasized in paper [28]), efficiency of the proposed solutions, in terms of "autonomous" and legal regulations. This is confirmed by the analysis of the results of the cause-effect relationships of the factors that characterize autonomous construction, indicating the lack of legislation and industry guidelines as the biggest threat to the development of the concept of earthship.

Looking at the current state of construction, it is hard to say that fully autonomous buildings will become a standard in the near future. Undoubtedly, it is noticeable that the needs of investors and users of a certain niche of the construction (residential) market are being met by earthships, built in various countries of the world. However, the trend of increase in the number of such buildings only in some aspects. These are:

– energy self-sufficient buildings (development of passive buildings, or even zero energy buildings),
– partially water and sewage self-sufficiency of buildings by using rainwater and/or grey water for processes that do not require it to be potable,
– independence from external services for wastewater treatment and biodegradable waste management in single-family buildings.

Investor interest is stimulated largely by legislative changes and subsidies for new solutions. Thus, it seems that this direction can be used to spread further aspects of self-sufficiency, e.g., related to waste management. This is confirmed by the authors of the publication [37] indicating the financial support as an important factor favouring the development of self-sufficient buildings.

References

[1] Główny Urząd Statystyczny, *Budownictwo w 2021 roku*. [Online]. Available: https://stat.gov.pl/obszary-tematyczne/przemysl-budownictwo-srodki-trwale/budownictwo/budownictwo-w-2021-roku,13,13.html. [Accessed: 30 May 2022].

[2] "Living conditions in Europe – housing – Statistics Explained", Eurostat Statistics Explained. [Online]. Available: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Living_conditions_in_Europe_-_housing#Key_findings. [Accessed: 30 May 2022].

[3] H. Borucińska-Bieńkowska, "Budownictwo mieszkaniowe a polityka funkcjonalno-przestrzenna – wybrane zagadnienia", *Builder*, vol. 279, no. 10, pp. 29–32, 2020, DOI: 10.5604/01.3001.0014.4020.

[4] T. Kaczmarek, *Stan, struktura przestrzenna i kierunki rozwoju mieszkalnictwa w aglomeracji poznańskiej październik 2015*. Centrum Badań Metropolitalnych, 2015.

[5] M. Chen Austin, K. Chung-Camargo, and D. Mora, "Review of zero energy building concept-definition and developments in Latin America: A framework definition for application in Panama", *Energies*, vol. 14, no. 18, art. no. 5647, 2021, DOI: 10.3390/en14185647.

[6] M. Celińska-Mysław and T. Wiatr, "Budownictwo zrównoważone z przykładem analizy kosztów w ujęciu LCC", *Przegląd Budowlany,* vol. 11, pp. 45-50, 2018. [Online]. Available: https://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-016c1030-69a5-459e-a0ee-7fc195d55a56. [Accessed: 30 May 2022].

[7] M. Szturo and M. Zapotoczna, "Green building-wyzwanie dla rynku nieruchomości mieszkaniowych (przypadek Olsztyna)", *Studia i Prace WNEiZ US*, vol. 42, pp. 233-243, 2015, DOI: 10.18276/sip.2015.42/2-20.

[8] M. Sitek, "View of Assessment of Sustainable Development of the Residential Construction Sector in the Context of Sustainable City Development in Poland", *European Journal of Sustainable Development*, vol. 7, no. 3, pp. 434-444, 2018, DOI: 10.14207/ejsd.2018.v7n3p434.

[9] Ň. Zaiats and V. Zaiats, "Housing Construction: Stages of Development and Modern Trends", *International Journal of Engineering and Technology,* vol. 7, no. 3.2, pp. 473-477, 2018, DOI: 10.14419/ijet.v7i3.2.14575.

[10] G. Grazieschi, et al., "Life cycle energy minimization of autonomous buildings", *Journal of Building Engineering*, vol. 30, 2020, DOI: 10.1016/j.jobe.2020.101229.

[11] Y. Zhang, et al., "A Survey of the Status and Challenges of Green Building Development in Various Countries", *Sustainability*, vol. 11, no. 19, art. no. 5385, 2019, DOI: 10.3390/su11195385.

[12] Centrum Badań i Analiz Rynku, *Raport. Budownictwo. Innowacje. Wizja liderów branży 2025*. Autodesk. [Online]. Available: https://unibep.pl/attachments/article/3296/Budownictwo.%20Innowacje.%20Wizja%20lider%C3%B3w%20bran%C5%BCy%202025.pdf. [Accessed: 30 May 2022].

[13] J.G. Backes and M. Traverso, "Application of life cycle sustainability assessment in the construction sector: A systematic literature review", *Processes*, vol. 9, no. 7, art. no. 1248, 2021, DOI: 10.3390/pr9071248.

[14] *Komunikat Komisji do Parlamentu Europejskiego, Rady, Europejskiego Komitetu Ekonomiczno-Społecznego i Komitetu Regionów Ramy polityczne na okres 2020–2030 dotyczące klimatu i energii / COM/2014/015 final*. 2014.

[15] *Komunikat Komisji do Parlamentu Europejskiego, Rady, Europejskiego Komitetu Ekonomiczno-Społecznego i Komitetu Regionów Plan działania w zakresie energii do roku 2050 /KOM/2011/0885 wersja ostateczna*. 2011.

[16] *Komunikat Komisji do Parlamentu Europejskiego, Rady, Europejskiego Komitetu Ekonomiczno-Społecznego i Komitetu Regionów Plan działania prowadzący do przejścia na konkurencyjną gospodarkę niskoemisyjną do 2050 r*. 2011.

[17] *Obwieszczenie Ministra Klimatu i Środowiska z dnia 30 listopada 2021 r. w sprawie szczegółowego wykazu przedsięwzięć służących poprawie efektywności energetycznej.*

[18] Sadowska Beata, J. R. Jimenez, and J. M. Fernández Rodriguez, "Modern building materials", in *Buildings 2020+: Constructions, materials and installations*, D. Krawczyk, Ed., Bialystok University of Technology, 2019, pp. 53-105, DOI: 10.24427/978-83-65596-71-0.

[19] *Rozporządzenie Ministra Transportu, Budownictwa i Gospodarki Morskiej z dnia 5 lipca 2013 r. zmieniające rozporządzenie w sprawie warunków technicznych, jakim powinny odpowiadać budynki i ich usytuowanie.*

[20] V.K. Burrows and E. Watson, "Advancing Net Zero Whole Life Carbon Offsetting Residual Emissions from the Building and Construction Sector", 2021. [Online]. Available: https://worldgbc.s3.eu-west-2.amazonaws.com/wp-content/uploads/2022/10/18110149/WorldGBC-Advancing-Net-Zero-Whole-Life-Carbon_PUBLICATION.pdf. [Accessed: 30 May 2022].

[21] A. Kuczera and M. Płoszaj-Mazurek, *How to decarbonice the built envirnoment by 2050 Whole life carbon roadmap for Poland*. PLGBC, 2021. [Online]. Available: https://plgbc.org.pl/wp-content/uploads/2021/06/Whole-life-carbon-roadmap-for-Poland-2050.pdf. [Accessed: 30 May 2022].

[22] J. Tomaszewska, D. Bekierski, and M. Piasecki, "Deklaracje środowiskowe wyrobów budowlanych narzędziem wspierającym rozwój zrównoważonego budownictwa", *Przegląd Budowlany*, vol. 88, no. 10, pp. 34–36, 2017. [Online]. Available: https://bibliotekanauki.pl/articles/162451. [Accessed: 30 May 2022].

[23] Zespół e-biurowce.pl., *Vademecum Zielone budynki w Polsce. Idea budowania zielonych biurowców – teoretyczne i praktyczne aspekty budownictwa zrównoważonego*. Kraków, 2011. [Online]. Available: https://www.e-biurowce.pl/uploads/ebook/pdf/d123049e510da30ff516d34af0bd89c518e7c8c4.pdf. [Accessed: 30 May 2022].

[24] M.M. Froufe, et al., "Smart buildings: Systems and drivers", *Buildings*, vol. 10, no. 9, art. no. 153, 2020, DOI: 10.3390/buildings10090153.

[25] D. Belani, et al., "Intelligent building new era of todays world attributes affecting success of the residential projects-a review view project construction management approach view project intelligent building new era of todays world", in *Conference on: "Trends and Challenges of Civil Engineering in Today's Transforming World"*. Civil Engineering Department S.N.P.I.T. & R.C., 2014, DOI: 10.13140/RG.2.1.1723.4965.

[26] J. Jura, "Wpływ budynków zeroenergetycznych i plusenergetycznych na emisyjność", *Budownictwo o Zoptymalizowanym Potencjale Energetycznym*, vol. 1 no. 13, pp. 33-40, 2014. [Online]. Available: http://yadda.icm.edu.pl/baztech/element/bwmeta1.element.baztech-bb842429-76e6-4b62-be11-85b1fc437185. [Accessed: 30 May 2022].

[27] U. Iyer-Raniga, "Zero Energy in the Built Environment: A Holistic Understanding", *Sciences*, vol. 9, no. 16, art. no. 3375, 2019, DOI: 10.3390/app9163375.

[28] P. Wyciślok and A. Wyciślok, "Ma'an – A new approach to the autonomous building," in *IOP Conference Series: Materials Science and Engineering*, vol. 960, art. no. 032104, 2020, DOI: 10.1088/1757-899X/960/3/032104.

[29] S.S. Nawale, "Autonomous Building", *International Journal of Engineering Research Development*, vol. 11, no. 11, pp. 22–24, 2015. [Online]. Available: http://www.ijerd.com/paper/vol11-issue11/Version_3/D5112224.pdf. [Accessed: 30 May 2022].

[30] Y.A. Mohammed, "A Review of Autonomous Buildings of the Future: Wisdom on Sustainable Design in Architecture and Engineering", *Current Trends in Civil & Structural Engineering*, 2019 vol. 2, no. 2, 2019, DOI: 10.33552/ctcse.2019.02.000534.

[31] Polska Organizacja Rozwoju Technologii Pomp Ciepła, *Poradnik „Dom bez rachunków"*. Kraków, 2019. [Online]. Available: https://dombezrachunkow.com/wp-content/uploads/2019/05/Poradnik_Dom_Bez_Rachunkow.pdf. [Accessed: 30 May 2022].

[32] S.-Y. Chen, et al., "The Autonomous House: A Bio-Hydrogen Based Energy Self-Sufficient Approach", *International Journal of Environmental Research and Public Health*, vol. 6, no. 4, pp. 1515–1529, 2009, DOI: 10.3390/ijerph6041515.

[33] M. Rygaard, P.J. Binning, and H.-J. Albrechtsen, "Increasing urban water self-sufficiency: New era, new challenges", *Journal of Environmental Management,* vol. 92, no. 1, pp. 185-194, 2011, DOI: 10.1016/j.jenvman.2010.09.009.

[34] D. Buehler, et al., "Towards Water and Energy Self-Sufficiency: a Closed-Loop, Solar-Driven, Low-Tech Laundry Pilot Facility (LaundReCycle) for the Reuse of Laundry Wastewater", *Circular Economy and Sustainability*, vol. 1, pp. 1037–1051, 2021, DOI: 10.1007/s43615-021-00077-2.

[35] H. Jouhara, et al., "Municipal waste management systems for domestic use", *Energy*, vol. 139, pp. 485–506, 2017, DOI: 10.1016/J.ENERGY.2017.07.162.

[36] E. Plebankiewicz, et al., "Models for estimating costs of public buildings maintaining-review and assessment", *Archives of Civil Engineering,* vol. 68, no. 1, pp. 335-351, 2022, DOI: 10.24425/ace.2022.140171.

[37] C.A. Booth, et al., "Insights into public perceptions of earthship buildings as alternative homes", *Buildings*, vol. 11, no. 9, 2021, DOI: 10.3390/buildings11090377.

[38] N.J. Kruis and M.K. Heun, "Analysis of the Performance of Earthship Housing in Various Global Climates", in *Proceedings of the ASME 2007 Energy Sustainability Conference. ASME 2007 Energy Sustainability Conference, 27-30 Jun 2007, Long Beach, California*. ASME, 2007, pp. 431–440, DOI: 10.1115/ES2007-36030.

[39] Twolking, *Earthship Welcome Center*. 3 Dec. 2021. [Photo]. Available: https://commons.wikimedia.org/wiki/File:Earthship_Welcome_Center.jpg. [Accessed: 16 Aug. 2022].

[40] D. Grubba, "Comparative analysis of earthships and conventional buildings in terms of investment and operating cost". Gdańsk, 2019, ISBN 978-83-60261-62-0. [Online]. Available: http://www.geomatyka.eu/publikacje/isbn9788360261620/isbn9788360261620.pdf. [Accessed: 26 May 2022].

[41] Energy Savings Trust, *Is the Earthship Model Viable as Affordable Eco-housing in Scotland? The Innovation Programme, Energy Saving Trust*. [Online]. Available: https://www.offgriditalia.org/files/documenti/Earthship_Report_oct04.pdf. [Accessed: 30 May 2022].

[42] S.-L. Si, et al., "DEMATEL Technique: A Systematic Review of the State-of-the-Art Literature on Methodologies and Applications", *Mathematical Problems in Engineering*, vol. 2018, art no. 3696457, 2018, DOI: 10.1155/2018/3696457.

[43] S. Rajput and S.P. Singh, "Connecting circular economy and industry 4.0", *International Journal of Information Management*, vol. 49, pp. 98–113, 2019, DOI: 10.1016/J.IJINFOMGT.2019.03.002.

[44] H.S. Lee, et al., "Revised DEMATEL: Resolving the infeasibility of DEMATEL", *Applied Mathematical Modelling*, vol. 37, no. 10–11, pp. 6746–6757, 2013, DOI: 10.1016/J.APM.2013.01.016.

[45] C.-W. Hsu, et al., "Using DEMATEL to develop a carbon management model of supplier selection in green supply chain management", *Journal of Cleaner Production*, vol. 56, pp. 164–172, 2013, DOI: 10.1016/j.jclepro.2011.09.012.

[46] A. Mach, "Analysis of the possibility of developing "earthship" autonomous buildings", *Civil and Environmental Engineering Reports,* vol. 32 no. 3, pp. 1-18, 2022, DOI: 10.2478/ceer-2022-0026.

Uwarunkowania rozwoju budynków samowystarczalnych

Słowa kluczowe: budynki samowystarczalne, earthships, eksploatacja, metoda DEMATEL, związki przyczynowo-skutkowe

Streszczenie:

Budowa i eksploatacja budynków charakteryzuje się zasobochłonnością w postaci masowego zużywania surowców i wyrobów, dużych nakładów finansowych i pracy ludzi, zużycia energii, wody, oddziaływania w długim okresie i znacząco na środowisko, w szczególności podczas ich użytkowania. Wdrażana aktualnie koncepcja zrównoważonego rozwoju i gospodarki cyrkulacyjnej ma wpływ na kierunki rozwoju budownictwa i wzmaga zainteresowanie budynkami samowystarczalnymi, w szczególności pod względem energetycznym, stosowania obiegów zamkniętych wody, wykorzystywania materiałów odpadowych. Celem artykułu jest analiza uwarunkowań rozwoju budynków samowystarczalnych. Na podstawie analizy literatury i badań rynku określono czynniki charakteryzujące tego typu budownictwo. Ich analiza za pomocą metody DEMATEL pozwoliła na ocenę i wskazanie najistotniejszych związków przyczynowo-skutkowych warunkujących rozwój budynków samowystarczalnych.

Z analizy współzależności między czynnikami wynika, że główną stymulantą rozwoju technologii domów samowystarczalnych, jest opracowanie norm technicznych i dostosowanie przepisów prawa do nietypowego charakteru budynków. Wpłynie to na zaangażowanie wszystkich uczestników

procesu budowlanego, w celu płynnego przejścia od budownictwa konwencjonalnego do autonomicznego.

Nietypowy projekt budowlany niesie za sobą wiele problemów na etapie realizacyjnym oraz uzyskiwania pozwoleń warto w procesie projektowania minimalizować negatywne oddziaływanie tego czynnika na przebieg procesu budowlanego, koszty, BIOZ oraz ograniczenia dotyczące położenia budynku.

Idea gospodarki o obiegu zamkniętym zakłada ponowne wykorzystanie odpadów, w procesie ich odzysku występuje jednak wiele trudności prawnych, środowiskowych i technicznych. Widoczna jest potrzeba opracowania racjonalnej ścieżki utraty statusu odpadów, które mogą stanowić bezpieczny materiał budowlany.

Wartości wskaźników istotności czynników (wag) potwierdzają, że słabe strony technologii, takie jak nietypowy projekt budynku oraz wykorzystanie materiałów odpadowych odgrywają największą rolę (barierę) w rozwoju technologii. Największą szansę dla rozwoju technologii stwarza widoczny wzrost zainteresowania życiem ekologicznym oraz wdrażanie zasad koncepcji zrównoważonego rozwoju I gospodarki cyrkularnej. Wspomniany trend wpływa pozytywnie na zmiany legislacyjne oraz dalszy rozwój technologii, co może w przyszłości zminimalizować słabe strony technologii.

Koncepcja budynków samowystarczalnych jest zgodna z obecnymi tendencjami rozwoju budownictwa mieszkalnego. Przede wszystkim w aspekcie uniezależnienia od usług świadczonych przez obiekty/organizacje publiczne, w świetle obecnej sytuacji geopolitycznej, a także (przy uwzględnieniu już na początkowym etapie projektu analizy LCA i LCC) wdrażaniu zasad budownictwa o obiegu zamkniętym. Mimo stosunkowo nienowej idei, wiele aspektów wciąż wymaga doskonalenia zarówno w zakresie kosztów, wydajności proponowanych rozwiązań jak i przepisów prawnych. Potwierdza to analiza wyników badań związków przyczynowo-skutkowych czynników charakteryzujących budownictwo samowystarczalne, wskazując brak przepisów prawnych I wytycznych branżowych jako największego zagrożenia dla rozwoju koncepcji obiektów typu „earthship”. Patrząc na obecny stan budownictwa, ciężko stwierdzić, aby w pełni samowystarczalne budynki w niedalekim czasie stały się standardem. Niewątpliwie obserwujemy spełnienie potrzeb inwestorów i użytkowników pewnej niszy rynku budowlanego (mieszkaniowego) za pośrednictwem earthshipów, budowanych w różnych krajach świata. Zauważyć jednak można, tendencję wzrostu ilości takich budynków tylko pod względem niektórych aspektów. Są to: samowystarczalnych pod względem energetycznym (rozwój budynków pasywnych, a nawet zero-energetycznych), częściowo autonomicznych poprzez wykorzystanie wody deszczowej i/lub szarej do procesów niewymagających jej przydatności do spożycia, uniezależnienie się od usług zewnętrznych w zakresie oczyszczania ścieków i zagospodarowania odpadów biodegradowalnych w budownictwie jednorodzinnym.

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