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Research paper

Analysis of the development possibilities of modular construction

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Abstract: The work reviews selected aspects of modular construction based on the literature that describes solutions used in residential and public buildings. The impact of construction on the environment and human health, as well as the time and cost of the investment, was considered. Design recommendations and preliminary assumptions for module dimensions are presented depending on the type of transport and type of structure. The types of structures and building materials used in modular buildings in Poland were collected, and then the parameter of the global warming potential of materials available in Europe was compared based on their declaration cards of environmental products. Based on the collected information, a brainstorming session was conducted between industry experts and scientists from the universities of technology to define the STEEPVL analysis factors, which identified several important factors that affect the development potential of modular construction in Poland. The results of the first analysis were then subjected to a structural analysis to identify key factors, purpose, determinants, and results. The result of the research was the preparation of proposals for current activities toward the future development of modular construction, with particular emphasis on the educational offer.

Keywords: design for disassembly, development potential, modular building, STEEPVL analysis, structural analysis

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1. Introduction

The constant need to build new buildings, while promoting efficient use of resources, leads to the search for solutions to reduce demand for: new building materials, energy, pollutant emissions, and financial resources. It is also important to increase the safety and comfort of employees. The construction method using prefabrication has been known for a long time, but in recent years there has been an increase in interest in advanced modular technology in the form of 3D volumetric structures. A modular building constructed in a factory with stable environmental conditions uses the same building materials for construction as those used in traditional construction [1]. Finished modules containing installations and sometimes also elements of equipment are transported to their destination and mounted on prepared foundations. At the construction site, there are connected joints, sometimes also finishing works and connections to the installation. The use of different types of structures makes it difficult to compare buildings from different manufacturers.

This article presents an overview of selected aspects of modular construction, with particular emphasis on the selection of building materials. The presented solutions are similar around the world (taking into account local environmental and legal differences, as well as the availability of materials and technologies) and are described in the example of solutions used in Poland. Based on a review of the currently used solutions, a STEEPVL (a method of strategic management) and structural analysis was conducted to identify factors influencing the possibilities for modular construction development in Poland.

2. Review of selected aspects of modular construction

A feature of the modules that make up the building is the repeatability of the shape, which facilitates the production and assembly process at the destination. By dividing the building design into modules of repeatable size, you can standardise the structural layout and MEP (MEP – mechanical, electrical and plumbing) location, making it easier to connect the modules later.

Modules can create a building structure on their own or make an addition to an existing facility. An interesting example of the use of a modular superstructure is presented by Tofiluk [2] – Loftcube designed as an independent structure that can stand on the foundation or on the roof of another building.

2.1. Investing duration

The advantage of prefabrication is that it speeds up the construction time. Using modular structures, even tall buildings can be built in a short time [3,4]. The rate of production depends on the type of structure and the capabilities of the factory, and the rate of assembly depends on the ability to deliver modules to the site. Oversized transport usually takes place at night when there is less traffic. In the case of multimodule buildings, the number of transporting cars must be coordinated with the pace of assembly. The initial method of connecting the elements (not including the subsequent finishing of the joints) is also important. Based on a review of 19 European examples, it was identified that on average a day it can be produced approximately 4 modules and assembled approximately 10 [5].

2.2. Impact on the environment

Kamali et al. [6] present a comparative analysis of the environmental impact of construction [6]. The construction of three single-family wooden frame residential buildings in Canada was compared: the first was built using the traditional on-site method and two others were built using modular technology. The three buildings had the same number and type of rooms, but differed in shape and usable area (the first one: 146 m^2, the second one: 138 m^2, the third one: 165 m^2. Many parameters of the LCA (LCA – Life Cycle Assessment) were analysed, which showed that the second building was the most sustainable in terms of environmental impact in relation to the entire construction process (cradle-to-gate). There were differences in the values of the individual parameters between both modular buildings, which could result from different construction methods of different companies and the difference in the size of the buildings. A traditionally constructed building had the least impact on human health at the stage of material production. It should be noted that all three buildings used different building materials and were constructed by different companies at different locations. For a more accurate comparative analysis, these parameters should be unified, but the results of the analysis are important because they show how many factors influence the final result of the calculation.

The proportions of carbon footprint emissions in the construction process (cradle-to-gate) of modular buildings are also presented by the research results of Hatmoko et al. [7], which show that the largest share – up to 94% of total emissions – comes from the raw material extraction stage, and transport is responsible for only 2.5%. Li [5], who estimates the impact of building materials production at 80%. By using wooden elements, the amount of CO_2 emissions can be balanced due to its absorption during tree growth. Kouhirostami et al. [8] recommend that to reduce the negative impact on the environment, local materials are used. In Poland, there is no obligation to calculate the carbon footprint of a building, and in Europe, only a few countries have introduced regulations on the analysis of the production stage of building materials (A1–A3) [9] and for this reason there are not enough data for detailed analyses of the environmental impact throughout the life cycle of a building constructed in Poland from local building materials. Estimated calculations can be made based on available EPD cards (EPD – environmental product declaration) for materials manufactured in Poland (are available for certain materials), and the missing data can be assumed based on EPD cards of materials manufactured in other European countries.

The currently promoted change from linear production to a circular economy requires an increase in the share of recycled building materials. In Europe, recycling in the construction industry is estimated at 30% [10]. When looking for further possibilities of reusing building materials, the philosophy of design for disassembly and reuse (Design for Disassembly – DfD) is considered [11]. The modular construction fits well into this model [5]. The segments produced in the factory from the beginning are prepared for transport, so after their period of use, they can be transported again to another place or returned to the factory for modification or renovation and reused. Individual building materials and elements can also be reused to produce subsequent modules [12].

2.3. Impact on human health

In addition to the impact on the environment, the impact on human health can also be analysed. Rey-Alvarez et al. [13] present the problem of comparing different materials due to the insufficient amount of data and different methods of determining them, suggesting that data should be compared using 1 kg as a unified unit. Analysing the potential impact on the development of cancer and non-cancer diseases, they ranked the structural materials in the following order, starting from the smallest impact: wood, concrete, glued laminated wood, reinforced concrete, steel. Structural wood is the bestFig solution in terms of carbon footprint and impact on human health. This is also confirmed by the publication by Kram et al. [14].

The ministerial order in force in Poland on the detailed scope and form of the construction project [15] specifies the obligation to prepare designed energy characteristics and attach analyses to them of the possibility of using available alternative energy sources [16], but this applies to installation systems, not building materials. Programmes supporting energy performance calculations allow one to calculate the amount of pollutants emitted by a building into the atmosphere [17].

2.4. Investment costs

A comparative analysis of construction costs using traditional and modular methods is difficult to perform due to technological differences, significant location, and inflation factors. The available data did not allow for a reliable assessment of the published information. According to a publication from 2022, the use of modular technology can reduce costs by 20% compared to traditional construction [18]. However, other studies show that modular technology can generate higher investment costs [3].

2.5. Projects

In the manual on the energy saving design of modular buildings, Pless et al. [19] recommend paying special attention to five components: thermal envelope, tightness of the envelope (infiltration), MEP systems (mechanical, electrical, and plumbing), smart system control, and solar energy storage.

The repeatability of the form of a component segment does not necessarily mean a simplification of the building's shape. Li et al. [5] compared 60 different modular structures made of modular structures for various purposes: offices, hotels, dormitories, residential buildings, schools, and hospitals and lists rectilinear, rotated, and non-orthogonal shapes, as well as embossed and recessed shapes. The size and weight of a single segment vary and are adjusted to the transport possibilities, most often they are:

- length 7.8 m, 6.7 m and 9.1 m,
- width from 3.1 m and 4.0 m,
- height from 3.0 m to 3.5 m,

and the mass (without equipment) of the modules is:

- with steel structure from 15 to 20 t,
- with concrete structure from 20 to 35 t,
- with wooden structure from 5 to 15 t.

Standard transport of large modules in Europe is limited to 12 m in length, 2.55 m in width, and 4 m in height, but there are differences between countries [5].

The above parameters are usually preliminary assumptions that should be taken into account at the stage of both the architectural concept and structural design.

The variety of solutions, on the one hand, is an advantage that allows the facility to be better tailored to the needs, but on the other hand, the multitude of parameters makes it difficult to compare solutions.

2.6. The size of modules used in Poland

The design of modular buildings is based on preliminary assumptions regarding transport possibilities in terms of dimensions, weight, and available methods of transfer from the car to the destination. Depending on the location of the plot and the network of access roads, transport can be carried out in various ways as shown in Fig. 1. If the dimensions or load on the axle exceed the permissible parameters specified in the regulation of transport on public roads [20] it is necessary to obtain a permit. Figure 1 also shows some examples of module sizes offered by Polish manufacturers.

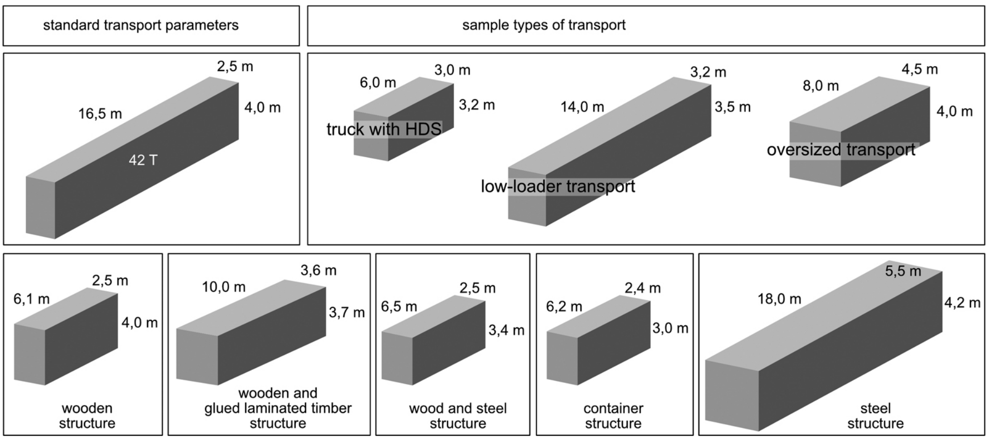


Fig. 1. Types of module transport [20, 21] and examples of module sizes [22–26]
(HDS – hydraulic truck crane)

2.7. Types of module structures used in Poland

Prefabricated modular structures are designed for durability during use and also during transport. The following types of module structure are available on the Polish market [22, 33]:

- steel based on the structure of a transport container,
- steel frame,
- wood-steel frame,
- wooden frame,

– frame made of laminated glued timber
– thin-walled reinforced concrete slabs glued at joints,
– reinforced concrete,
– polymer composites,
– combined of the above (in various combinations).

Manufacturers offer facilities designed for various functions, including year-round residential buildings. It is possible to combine several connected modules horizontally and vertically and to create the required angle of inclination of the roof. Adapting the architectural concept to modular construction and the structure are designed individually depending on the type of technology and the selected method of transport and assembly. In subsequent projects, the experience gained in previous projects and from the production stage is used and the technology is improved by striving for the typification of repeatable elements. The design should meet the same standard and statutory requirements as for traditionally constructed buildings, and additionally take into account transport and assembly loads.

2.8. Building materials used in Poland

The building materials used in modular construction are analogous to those used in traditional technology. The most frequently used are [22–32]:

– for structural elements: cold bent or rolled steel profiles, glued KVH (KVH is a kiln-dried finger joint product made of solid softwood and is strength-graded) and LVL (Laminated veneer lumber) glued timber, C24 spruce wood C24, reinforced concrete,
– for stiffening elements: OSB board (OSB – Orientated Strand Board), MFP board (MDF boards are made of wood fibres bonded by synthetic resin and compressed through pressure and heat), galvanised steel board, trapezoidal steel sheet, fibre-cement board,
– for elements protecting the floor against rodents or against swelling in the event of flooding: aluzinc sheet, trapezoidal steel sheet, fibre-cement board,
– as thermal and acoustic insulation (also in the form of traditional sandwich panels and SIP panels, SIP – structural insulated panels): rock wool, glass wool, graphite polystyrene, PIR, PUR (PIR – polyisocyanurate, PUR – polyuretane), wood wool, straw cellulose, aluminium foil,
– vapour barrier and vapour permeable foils,
– for roof covering: sheet metal (flat sheets and metal roofing tiles), roofing felt shingles, EPDM foil (EPDM – Ethylene Propylene Diene Monomer),
– as facade finishing material: impregnated or painted boards, metal sheet, plaster (ETICS system, ETIS – External Thermal Insulation Composite System), composite boards, fibre cement boards, facade stone,
– as internal finishing material: plasterboard (different types depending on the purpose of the room), fireproof board.

Most structures are designed to be placed on point foundations of concrete or screw-in steel, but sometimes also on a concrete slab. Due to the low weight of the modules, they can also be a superstructure of existing buildings (provided there is sufficient load-bearing capacity).

The carbon footprint of individual building materials used in modular construction may vary depending on the production method and the percentage of recycled raw materials used. Figures 2– 4 show the GWP (Global Warming Potential – GWP) ranges based on EPDs for materials manufactured in Europe.

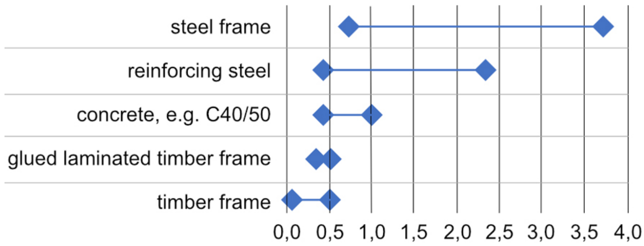


Fig. 2. Ranges of GWP [kg CO_2–e/kg] values for materials used for structural elements [own study based on EPD cards]

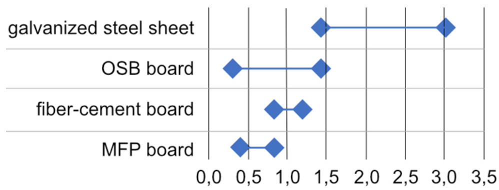


Fig. 3. Ranges of GWP [kg CO_2–e/kg] values for materials used for stiffening and finishing elements [own study based on EPD cards]

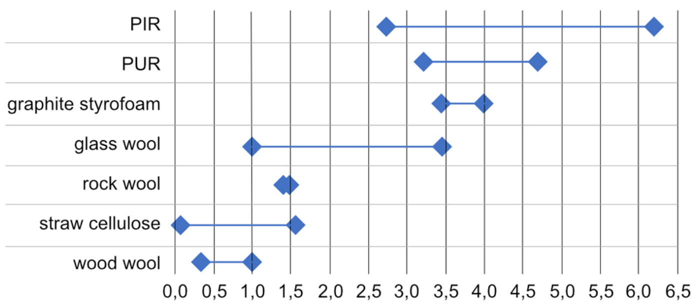


Fig. 4. Ranges of GWP [kg CO_2–e/kg] values for materials used for thermal insulation elements [own study based on EPD cards]

Some types of materials have a wide range of GWP values, but despite this, differences in the value ranges can be observed, which can be helpful when deciding on solutions.

3. The potential for the development of modular construction in Poland

Interest in modular construction is observed in many countries and, as Szulc et al. noted in 2020 [34], its development is also taking place in Poland [35]. The positive aspects of this technology are the ability to save time and costs, as well as greater predictability of the construction process [33, 36]. In particular, the aspect of reducing construction time was appreciated in the years 2020–2021, when there was a need to build health care facilities quickly [37]. The short construction time is also useful for expanding educational facilities to meet current needs [38]. A problem that may hinder the popularisation of modular construction is the lack of consistent standards for shaping elements [39], which in the case of prefabricated construction provides a greater opportunity to compare and select offers. The development of innovative solutions for prefabricated construction [40], including modular ones, is consistent with the development strategy in Poland and is supported, that is, by the NCBiR project [41]. The development of modular technologies is also observed in the search for non-standard solutions, e.g., trombe wall [42] or the use of SIP panel [43]. Attention is also paid to the impact of contractor skills on the success of construction and the implementation of a high level of quality assurance from the design stage to execution [44].

In search of directions for the development of modular construction in Poland, qualitative research was adopted as part of the foresight method. The purpose of the research was to identify key and regulatory aspects influencing the development potential of modular construction in Poland. The starting point for selecting the analysed factors was a literature review, brainstorming sessions, expert panels, conferences, and workshops attended by representatives of science and entrepreneurs familiar with the industry. The planned research was divided into two stages: STEEPVL analysis and structural analysis.

3.1. Results of the first stage of the investigation

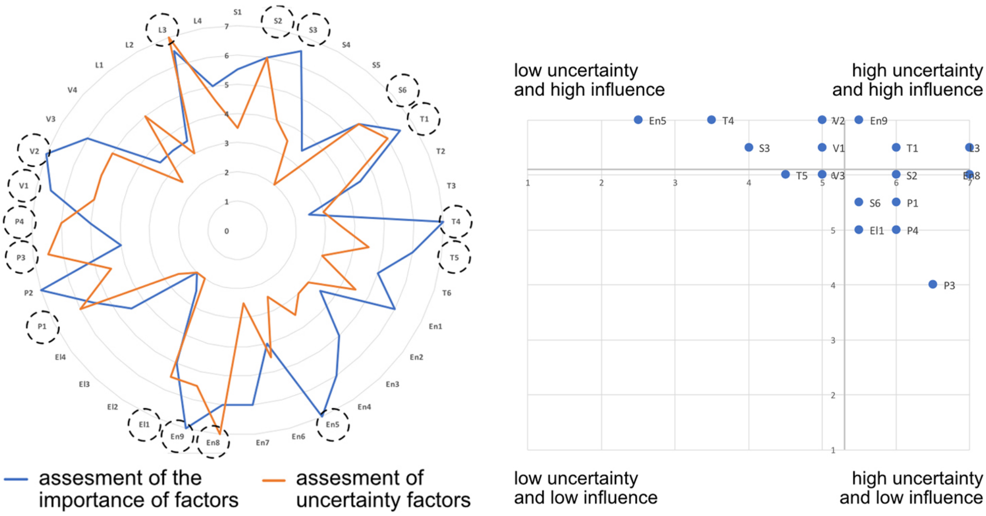
On the basis of brainstorming, the factors influencing the studied area were formulated and divided into groups: social (S), technological (T), economic (EN), ecological (EL), political (P), values (V), and legal (L). Based on survey research, factors' importance and uncertainty were evaluated. The results are presented in Fig. 5a. A seven-point rating scale was adopted:

– for the importance of factors (influence): 1 – very little influence, and 7 – very great influence,
– for uncertainty: 1 – very small uncertainty and 7 – very large uncertainty.

The results were analysed by an expert panel and the most important factors in each group were selected. Selected factors are presented in a chart that compares importance and uncertainty (Fig. 5b). The average value of the importance ratings is 6.1 and the uncertainty is 5.3.

The factors with the greatest influence and the greatest uncertainty are:

– L3: legal regulations enabling the expansion / disassembly of modules depending on current needs,
– T1: the need to maintain high precision in production and assembly,
– En9: availability of investment financing.



(a) (b)

Fig. 5. Results of the STEEPVL analysis: a) average values for assessing the importance and uncertainty of factors; the marked factors were selected as the most important, b) comparison of the importance and uncertainty of factors (own study)

3.2. Results of the second stage of the investigation

Factors selected as important in the first stage of the research were used in the structural analysis, examining mutual influences between individual factors. Figure 6 shows the network of indirect interactions for the 5% strongest interactions.

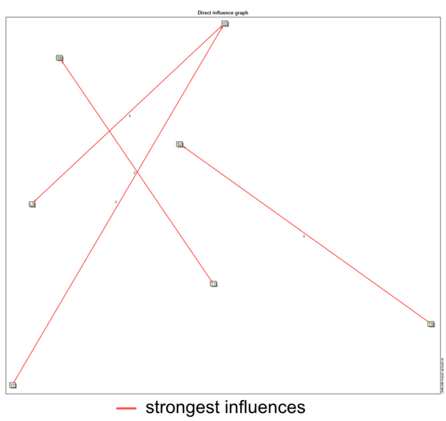


Fig. 6. Structural analysis – network of direct interactions (the figure shows the strongest 5% of interactions) (own work in the MICMAC programme)

The following factors have the strongest impact:
- T1 (need to maintain high precision of production and assembly) to S6 (possibility of expanding/disassembling modules depending on changing needs),
- V1 (utility attractiveness of modular buildings) to V2 (carefulness in design and the ability to predict assembly possibilities),
- V2 (careful design and the ability to predict assembly possibilities) to L3 (legal regulations enabling the expansion / disassembly of modules depending on current needs),
- T5 (availability of transport and assembly equipment adapted to large and heavy modules) to S2 (large number of companies producing modular buildings).

Figure 7 groups the factors into the following types:
- key with high influence and high dependence,
- goals, dependent to a greater extent on others and changing under their influence,
- results with low impact and high dependency,
- determinants (motors or brakes) – very high impact and low dependence,
- regulating and auxiliary with little impact,
- external having a minor impact, smaller than determinants, but greater than autonomous factors,
- No autonomous factors with the smallest influence were obtained.

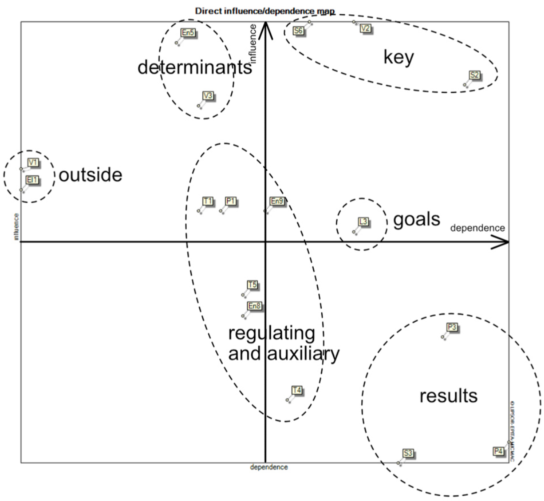


Fig. 7. Structural analysis – Grouping factors on the influence dependence chart in the study of direct influences (own work and in the MICMAC programme)

The following factors were identified as key:
- S2 – a large number of companies producing modular buildings,
- V2 – careful design and the ability to predict assembly possibilities,
- S6 – possibility of expanding/disassembling modules according to changing needs.

The goal is the L3 factor – legal regulations enabling the expansion/disassembly of modules depending on current needs.

The results are factors:
- P3 – state innovation development policy,
- S3 – demand for new buildings,
- P4 – EU recycling policy.

The following factors were identified as determinants:
- V3 – openness to new things/innovations,
- En5 – faster construction time giving faster return on investment.

3.3. Results analysis

The analyses carried out identified issues that may be key in the development of modular construction in Poland.

An important factor may be an increase in the number of companies that offer building production using modular technology (S2). The contractor's offer in the field of construction is a response to market demand, and currently this type of construction production is not widely used. The trends promoted in the European Union to increase recycling in construction will also force changes in Polish regulations in this area. The use of modular construction, i.e. design for deconstruction, may be one of the ways to meet the above described requirements, which may give an impetus to the development of construction companies towards modular construction.

A key factor according to structural analysis is careful design and the ability to predict the possibilities of assembly (V2). Preparing the basis for the development of construction and design companies in the future should involve advance preparation of staff, so training methods for designers and construction contractors in modular technology should currently be developed and implemented. The training offer should be addressed not only to students of technical schools and universities but also to professionally active engineers through training offered by chambers and associations. Training should be addressed to designers of architecture, structures, and installations. Due to the specificity of assembly, training should be prepared and conducted in cooperation with contractors experienced in the design, manufacture, and assembly of modular buildings. Training of construction industry employees will not only increase their knowledge and skills, but may also help change the beliefs of customers who will be offered construction using modular technology.

Another key factor is the ability to expand/dismantle modules depending on changing needs (S6). The possibility of rebuilding an existing building is currently allowed under Polish law, and modular buildings can also be used for expansion. The aim of activities that promote modular construction should be to bring about changes in the legal regulations (L3) that facilitate the procedure related to demolition and expansion using modular technology, especially in public buildings. Today, the construction of schools or transport infrastructure (passenger service points on public transport of facilities) is usually associated with targeted funding, and each change in the size of the building is a separate procedure. Large companies, e.g. railways, with many buildings in many locations, using modular solutions, could constantly adjust the size of buildings to the demand in a given place by moving modules from locations where the number of travellers has decreased to a place where they are increasing. This method of property management would result in fewer losses resulting from the need to maintain buildings that are no longer needed, and when moving the module to a new location, they could also be modernised using recycled materials and devices dismantled in other locations. This approach would require the company to have warehouse space and to cooperate with factories that carry out module renovations and modernizations, while providing them with a constant offer of orders, which will contribute to the development of the factories.

The result of these activities may be the demand for new buildings that use modular technology. Changing the way buildings are managed using removable modules is part of the European Union's recycling policy (P4) and may be a sign of the country's innovation (P3). In order to popularise modular construction, it is necessary to increase accessibility of transport and assembly devices adapted to large and heavy modules should also increase.

A factor that has a significant impact on the development of modular construction is the encouragement of potential investors. Customers' openness to new things (V3) must be linked to trust in designers and contractors, which results from their practical experience. An additional advantageous aspect from the customer's point of view is the ability to speed up the construction process and become independent of weather influences, which in the case of an investment gives it a faster return (En5).

4. Summary

The aim of the work was to answer the question of the possibilities of developing modular construction in Poland. A review of the currently used construction and material solutions and transport options was performed.

An overview of the described aspects of modular construction gives insight into the diversity of solutions used. The types of modular structures are the same as in traditional construction and require an individual approach to design and construction. The advantage of modular solutions may be their repeatability and organisation of work in the factory, eliminating downtime, which may result in faster production. Better employee education will result in a better work organisation, so you should invest in the development of current and future staff.

A challenge in the development of modular construction may be the transport of modules from the point of view of the availability of vehicles that carry large loads. Additionally, it would be necessary to extend the analyses in terms of patency to large road loads in Poland and, on this basis, recommend the external dimensions of the modules.

Modules are designed not only for use but also for transport. Using this feature allows you to join the circular economy. After a period of use or if a change is necessary, the module can be transported to the factory and rebuilt with another one. During redevelopment, some building materials can be recovered for use in another building or for recycling. The environmental impact can also be reduced by carefully selecting a building material with a lower GWP. The analyses should be extended to include a more detailed comparison of the load-bearing capacity of various types of structures and the quantitative consumption of materials.

For an investor, the speed of return on investment is important. Thanks to modular technology, the time can be reduced because the foundations are made at the same time as the construction. Modules built in a dry factory environment also have less built-in moisture, so they can be put into use faster. The analyses did not specify the investment cost aspect, but it can be assumed that as the popularity of modular construction increases and competition develops, the price will decrease. Cost analyses should be expanded to take into account differences resulting from local conditions.

On the basis of the collected data and the practical knowledge of experts, research was carried out using strategic management methods. The analysis results focus on areas that require development. To popularise modular construction, the number of builders should increase. Today, prefabrication is developing. It should be examined whether existing factories of prefabricated elements, e.g., reinforced concrete, could expand their offer to include other types of structures, or whether it would be more beneficial to build new factories dedicated to steel or wooden structures. The factory's specialisation only applies to the type of construction, because the remaining materials (insulation, installation, and finishing) are the same regardless of the type of construction. Another aspect to consider is the location of factories to shorten the transport of finished modules.

Changing the method of constructing a building from the traditional to the modular method may be an opportunity for the development of construction companies and contribute to the increase in innovation in the construction sector in Poland. The condition for these changes is the adaptation of regulations simplifying the disassembly and expansion procedure, educating designers and contractors in cooperation with modular construction factories, and convincing investors that the technology used can give them a faster return on investment.

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References

[1] "What is Modular Construction?". [Online]. Available: https://www.modular.org/what-is-modular-construction/. [Accessed: 20. Dec. 2023].

[2] A. Tofiluk, "Problems and challenges of the built environment and the potential of prefabricated architecture", *Archives of Civil Engineering*, vol. 69, no. 3, pp. 405–424, 2023, doi: 10.24425/ace.2023.146088.

[3] K. Gharehbaghi, E. Mulowayi, F. Rahmani, and D. Paterno, "Case studies in modular prefabrication: comparative analysis and discoveries", *Journal of Physics: Conference Series*, vol. 1780, 2021, doi: 10.1088/1742-6596/1780/1/012009.

[4] H.-T. Thai, T. Ngo, and B. Uy, "A review on modular construction for high-rise buildings", *Structures*, vol. 28, pp. 1265–1290, 2020, doi: 10.1016/j.istruc.2020.09.070.

[5] J. Li, L.V. Andersen, and M.M. Hudert, "The Potential Contribution of Modular Volumetric Timber Buildings to Circular Construction: A State-of-the-Art Review Based on Literature and 60 Case Studies", *Sustainability*, vol. 15, no. 23, 2023, doi: 10.3390/su152316203.

[6] M. Kamali, K. Hewage, and R. Sadig, "Conventional versus modular construction methods: A comparative cradle-to-gate LCA for residential buildings", *Energy in Buildings*, vol. 204, 2019, doi: 10.1016/j.enbuild.2019.109479.

[7] J.U.D. Hatmoko, M.A. Wibowo, and F. Prasetyo, "Carbon Emissions Analysis of Modular House Construction", *Web of Conferences*, vol. 448, 2023, doi: 10.1051/e3sconf/202344803040.

[8] M. Kouhirostami, A.R. Chini, and R.J. Ries, "Evaluating the GHG Emissions of Manufactured Housing through a Comprehensive Life-Cycle Assessment", in *Conference ASCE Inspire 2023: Infrastructure Innovation and*

Adaptation for a Sustainable and Resilient World, 16–18 November 2023, Arlington, US. ASCE Library, 2023, pp. 867–876, doi: 10.1061/9780784485163.100.

[9] "Review of european LCA regulations", in *Construction carbon regulations in Europe. Review & Best Practises*, One Click LCA, 2022, pp. 39–47. [Online]. Available: https://143253260.fs1.hubspotusercontent-eu1.net/hubfs/143253260/EU Regulations Review.pdf. [Accessed: 20. Mar. 2024].

[10] "The built environment in Europe and the world", in *A Circular Future for the European Construction Sector: Light Commercial and Residential Buildings*, Circle Economy and Bain & Company, 2022, pp. 6–7. [Online]. Available: https://www.circle-economy.com/resources/a-circular-future-for-the-european-construction-sector-light-commercial-and-residential-buildings. [Accessed: 20. Mar. 2024].

[11] J. Jayawardana, M. Sandanayake, A.K. Kulatunga, J.A.S.C. Jayasinghe, G. Zhang, and S.A.U. Osadith, "Evaluating the Circular Economy Potential of Modular Construction in Developing Economies – A Life Cycle Assessment", *Sustainability*, vol. 15, no. 23, 2023.

[12] F.E. Boafo, J.-H. Kim, and J.-T. Kim, "Performance of Modular Prefabricated Architecture: Case Study-Based Review and Future Pathways", *Sustainability*, vol. 8, no. 6, 2016, doi: 10.3390/su8060558.

[13] B. Rey-Alvarez, J. Silvestre, A. Garcia-Martinez, and B. Sanchez-Montanes, "A comparative approach to evaluate the toxicity of building materials through life cycle assessment", *Science of the Total Environment*, vol. 912, 2024, doi: 10.1016/j.scitotenv.2023.168897.

[14] D. Kram, K. Nowak, K. Śliwa-Wieczorek, H. Hrehorowicz-Gaber, R. Błazy, A. Hrehorowicz-Nowak, J. Błachut, M. Łysień, A. Ciepiela, and J. Dudek, "Wooden modular construction as an innovative solution for schools of the future", *Materiały Budowlane*, no. 12, pp. 27–32, 2023, doi: 10.15199/33.2023.12.06 (in Polish).

[15] Regulation of the Minister of Development of September 11, 2020 on the detailed scope and form of the construction project, Dz. U. z 2020 r. poz. 1609. [Online]. Available: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU20200001609. [Accessed: 20. Dec. 2023]. [Accessed: 20. Dec. 2023] (in Polish).

[16] "Energy performance certificates", bape.com. [Online]. Available: https://bape.com.pl/oferta/swiadectwa-charakterystyki-energetycznej/. [Accessed: 20. Dec. 2023] (in Polish).

[17] "Economic and ecological effect", www.warcholcertyfikacja.pl, [Online]. Available: https://warcholcertyfikacja.pl/efekty.html. [Accessed: 20. Dec. 2023] (in Polish).

[18] J. Pasławski and K. Włoch-Surówka, "Modular construction as a possibility of flexible adaptation to user requirements on selected examples", *Materiały Budowlane*, vol. 12, pp. 53–55, 2022, doi: 10.15199/33.2022.12.14 (in Polish).

[19] S. Pless, A. Podder, Z. Kaufman, N. Klammer, C. Dennehy, N.K. Muthumanickam, S. Rothgeb, J. Louis, C. Swanson, H. Wallace, and C. Blazek, "The energy in modular (EMOD) buildings method: A guide to energy-efficient design for industrialized construction of modular buildings", Technical Report: NREL/TP-5500-82447, Jun. 2022, doi: 10.2172/1875070.

[20] Road Traffic Law, Act of 20 June 1997, Dz.U. 1997 nr 98 poz. 602. [Online]. Available: https://isap.sejm.gov.pl/isap.nsf/DocDetails.xsp?id=WDU19970980602 (in Polish).

[21] "What is oversize transport?", orck.pl. [Online]. Available: https://www.ocrk.pl/transport-ponadgabarytowy/. [Accessed: 20. Dec. 2023] (in Polish).

[22] "Technology. Steico construction system", westarte.pl. [Online]. Available: https://www.westatre.pl/technologia/. [Accessed: 20. Dec. 2023] (in Polish).

[23] "Modular houses", dreammobilhouse.pl, [Online]. Available: https://dreammobilhouse.pl/domy-modulowe/. [Accessed: 20. Dec. 2023] (in Polish).

[24] "What is Modulex modular container technology?", modulex-eu.pl, [Online]. Available: https://modulex-eu.pl/technologia-modulex/modularna-technologia-kontenerowa-modulex/. [Accessed: 20. Dec. 2023] (in Polish).

[25] " Ecological modular technology", biodomek.pl, [Online]. Available: https://www.biodomek.pl/technologia. [Accessed: 20. Dec. 2023] (in Polish).

[26] "Structure of the modules", climatic.pl. [Online]. Available: https://climatic.pl/konstrukcja/. [Accessed: 20. Dec. 2023] (in Polish).

[27] "Technology. Description of the standard", imshouse.pl. [Online]. Available: https://www.imshouse.pl/. [Accessed: 20. Dec. 2023] (in Polish).

[28] "Modern construction solutions – modular wooden houses, modular offices", modulowydom.pl. [Online]. Available: https://modulowydom.pl/. [Accessed: 20. Dec. 2023] (in Polish).
[29] "Year-round modular houses", fasthome.com.pl. [Online]. Available: https://fasthome.com.pl/. [Accessed: 20. Dec. 2023] (in Polish).
[30] "Modular houses made of sandwich panels", ramal.pl. [Online]. Available: https://www.ramal.pl/oferta/domy-modulowe. [Accessed: 20. Dec. 2023] (in Polish).
[31] "Technology", mojdomek.pl. [Online]. Available: http://mojdomek.pl/technologia/. [Accessed: 20. Dec. 2023] (in Polish).
[32] "Modular construction", perfectcube.pl. [Online]. Available: https://perfectcube.pl/site.php?show=technologia. [Accessed: 20. Dec. 2023] (in Polish).
[33] T. Piotrowski, P. Woyciechowski, and G. Adamczewski, "Prefabricated modular construction", *Materiały Budowlane*, no. 4, pp. 50-53, 2022, doi: 10.15199/33.2022.04.09 (in Polish).
[34] J. Szulc and J. Sieczkowski, "The future of modular technologies in construction", *Inżynier Budownictwa*, no. 5, pp. 82-86, 2020 (in Polish).
[35] A. Plis and K. Prałat, "Modular construction as a response to contemporary challenges", *Przegląd Budowlany*, no. 7-8, pp. 151-154, 2023, doi: 10.5604/01.3001.0053.8513 (in Polish).
[36] L. Runkiewicz, J. Szulc, and J. Sieczkowski, "The evolution of prefabricated construction in Poland", *Przegląd Budowlany*, vol. 91, no. 10, pp. 12-15, 2020 (in Polish).
[37] R. Gliwa and K. Gerlic, "Modular architecture in the fight against the epidemic – experiences of 2020", *Builder Science*, vol. 285, no. 4, pp. 72–74, 2021, doi: 10.5604/01.3001.0014.7955 (in Polish).
[38] R. Blazy, H. Hrehorowicz-Gaber, J. Błachut, A. Ciepiela, M. Łysień, J. Dudek, and A. Hrehorowicz-Nowak, "Planning aspects of locating the modular Green Class system for selected schools in Krakow", *Builder Science*, vol. 317, no. 12, pp. 100–109, 2023, doi: 10.5604/01.3001.0054.0135 (in Polish).
[39] P. Sulik and Ł. Zawiślak, "Modular construction as a modern prefabrication technology", *Inżynier Budownictwa*, vol. 12, pp. 56–61, 2021. [Online]. Available: https://www.piib.org.pl/inzynier-budownictwa/2021 (in Polish).
[40] J. Pasławski and K. Włoch-Surówka, "Modular construction adapted to changing requirements on the example of railway stations", *Materiały Budowlane*, vol. 605, no. 1, pp. 4–9, 2023, doi: 10.15199/33.2023.01.03 (in Polish).
[41] P. Kopacz and A. Węglarz, "Innovative modular construction technologies", *Budownictwo i Prawo*, no. 3, pp. 3–6, 2022 (in Polish).
[42] V. Zhelykh, M. Ulewicz, Y. Furdas, and V. Shepitchak, "Investigation of thermal and air efficiency in trombe wall of modular building", *Archives of Civil Engineering*, vol. 69, no. 4, pp. 663-678, 2023, doi: 10.24425/ace.2023.147682.
[43] M.Y. Khan, A. Baqi, and R. Sadique, "Thermal and acoustic behavior of energy saving wall panel", *Archives of Civil Engineering*, vol. 67, no. 4, pp. 303–316, 2021, doi: 10.24425/ace.2021.138501.
[44] W. Pan, D. Parker, and M. Pan, "Problematic interfaces and prevention strategies in modular construction", *Journal of Management in Engineering*, vol. 39, no. 2, 2023, doi: 10.1061/JMENEA.MEENG-5083.

Analiza możliwości rozwoju budownictwa modułowego

Słowa kluczowe: analiza STEEPVL, analiza strukturalna, budownictwo modułowe, potencjał rozwojowy, projektowanie z myślą o demontażu

Streszczenie:

W pracy dokonano przeglądu wybranych aspektów budownictwa modułowego na podstawie literatury opisującej rozwiązania stosowane w budynkach mieszkalnych i użyteczności publicznej. Uwzględniono wpływ budowy na środowisko i zdrowie ludzi, a także czas i koszt realizacji inwestycji. Przedstawiono zalecenia projektowe i wstępne założenia dotyczące wymiarów modułów, w zależności od rodzaju transportu i rodzaju konstrukcji. Zebrano rodzaje konstrukcji i materiałów budowlanych, stosowanych w budynkach modułowych w Polsce, a następnie porównano potencjał tworzenia efektu cieplarnianego materiałów dostępnych w Europie na podstawie kart deklaracji środowiskowych. Na podstawie zebranych informacji przeprowadzono burzę mózgów pomiędzy ekspertami branżowymi i naukowcami z uczelni technicznych w celu zdefiniowania czynników analizy STEEPVL identyfikujących istotne czynniki wpływające na potencjał rozwojowy budownictwa modułowego w Polsce. Wyniki pierwszej analizy poddano następnie analizie strukturalnej w celu zidentyfikowania kluczowych czynników, celu, determinant i wyników. Efektem badań było przygotowanie propozycji bieżących działań na rzecz przyszłego rozwoju budownictwa modułowego, ze szczególnym uwzględnieniem oferty edukacyjnej.

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