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Modular houses as a form of sustainable construction

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Abstract: The article discusses the currently developing technology for building economical and energy-saving modular houses. Based on the literature analysis of historical and new modular construction solutions, an attempt was made to classify modular houses and the advantages and disadvantages of individual construction systems were presented. The authors present modern modular house systems, pointing to innovative, ecological and energy-saving construction solutions that meet the criteria of sustainable construction.

Keywords: modular houses, small houses, sustainable construction

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Introduction

One of the forms of modern housing construction that differs from the traditional method of constructing buildings from small-sized elements is the modular method of building houses. The assembly of ready-made walls, ceilings and other elements constituting the building structure is much faster than in the case of traditional construction carried out on the construction site. The increased interest in modular houses from developers and individual investors is due to the fact that they are the fastest and shortest way to build a house, and the total construction cost is known at the time of concluding the contract and is usually much lower than the costs of construction using traditional technology.

Modular houses are prefabricated buildings or sectional houses composed of many sections called modules (Ganiron & Almarwae, 2014). The modules are constructed

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in the production plant and then delivered to their destination, where they are placed on a foundation and combined into one building.

The first mention of a modular building appeared in 1837 in the London newspaper The South Australian Record (Ganiron & Almarwae, 2014). In the mid-19th century, hundreds of Manning buildings were constructed in Australia with prefabricated elements manufactured in London and shipped to Australia.

Another milestone in the development of modular construction is the prefabricated wooden Renkioi Hospital for 1,000 patients, created in 1855, sometimes called the Florence Nightingale Hospital. A famous English nurse and activist, distraught by the poor conditions in the field hospital where she served during the Crimean War, wrote a letter to the London Times, asking for help. Five months later, a modular hospital designed by Isambard Kingdom Brunel was sent to Crimea.

Further forms of the modular house appeared in the 1920s, due to the development of the need to have a house with all the technical installations and furniture, and at the same time capable of transport. The solution to this problem was the so-called mobile home, designed for transport and with additional reinforcements to withstand several moves during their use (Bonds & Bramwell, 2002).

The modular construction industry gained enormous popularity after World War II in America, when war veterans returned home, but due to the lack of money and work, they had to look for work in different locations, and therefore their houses had to be cheap and mobile. Modular homes manufactured by the Sears Roebuck Company in the 1940s were very popular in America, among people moving to California for The Gold Rush (Ganiron & Almarwae, 2014).

Due to the development of maritime transport using containers for loading and transporting goods, there have also been attempts to use containers in construction. Initially, they were used as temporary constructions, and in subsequent years also as service, commercial and residential facilities (Szulc & Sieczkowski, 2020). Dimensional coordination based on the use of modules, i.e. conventional units of linear measurement, was called modular coordination (Ganiron & Almarwae, 2014).

In the 1960s, investors' requirements for comfort increased, and with them the functionality of modular houses increased and new material and construction solutions appeared. There are three basic types of structural systems for modular buildings (Matysiak, 2022):

- Houses in a frame system consisting of columns, beams and ceiling slabs. Frame structures were designed mainly from wood, steel or aluminum and, less frequently, from concrete. One of the first modular house concepts in this system was the Dom-Ino-House developed by Le Corbusier in a system based on standardized beams and columns.
- Houses in the panel system with a structure composed of prefabricated flat wall and ceiling elements. The panels could be wooden, steel, reinforced concrete, sandwich or mixed. The original example of a single-family house designed in this system is the Furniture House in Tokyo designed by Shigeru Bana.
- Buildings composed of three-dimensional modules with a prefabricated structure. These are residential complexes composed of concrete, cuboid residential modules arranged around reinforced concrete cores, e.g. Habitat 67 and

Nakagin Tower. Two types of systems using three-dimensional modules can be distinguished: portable micro-residential units that create larger complexes and objects with dimensions similar to a typical single-family house, in which individual elements are different rooms or groups of rooms (Matysiak, 2022).

Currently, with the emergence of the idea of sustainable development, a new architectural trend has appeared called Tiny Houses, consisting of residential buildings with a very limited living space, but functional and meeting all physical and mental needs. In highly developed regions, where residents experience the inconvenience of living in a highly urbanized space, attempts are made to locate small houses in direct contact with nature. A variation of Tiny Houses are mobile homes built in a factory and then placed on a trailer chassis to allow them to be moved freely (Wyrzykowski, 2019).

1. Construction systems used in modular construction

Modular houses are assembled from ready-made prefabricated elements constituting larger parts of buildings. With the exception of mobile homes, in very few cases an entire prefabricated block house is transported and assembled on foundations (Ganiron & Almarwae, 2014). Mobile homes have a structure that is entirely attached to the chassis frame on wheels, or they have reinforcements that allow them to be lifted with a crane and placed on the platform of a semi-trailer intended for oversized loads. Due to the requirements of transport and assembly with a crane, block houses have simple forms and size limitations.

Single-block prefabricated houses are fully prefabricated and equipped with furniture and technical installations (Ganiron & Almarwae, 2014). The time to complete the assembly of such a house is much shorter compared to other modular house systems. Typically, modules are manufactured in a factory in the form of smaller prefabricated elements, which must be properly connected on the construction site to create the final building structure. Modules in the form of cuboids with a self-supporting structure can be placed next to each other or stacked, which allows for a wide range of configurations and building layout styles. One module may constitute one room, and the rooms may have different functions (Liang & Mengxuan, 2021).

Block modules with a steel structural frame are also used to construct multi-story buildings (Generalova et al., 2016). This requires additional work related to the connection of blocks and the construction of a ventilated façade, e.g. from metal panels made of galvanized steel with a polymer coating, giving the building a modern look. In the case of single-family houses according to individual projects, after connecting spatial modules, they may be subject to different static patterns. If modules are combined with overhangs, it is necessary to create an additional supporting structure (Liang & Mengxuan, 2021). Nowadays, except for attempts made by individual investors, sea containers are no longer used in housing construction. However, prefabricated block reinforced concrete elements are still produced and are used only for the construction of multi-story buildings.

Other technologies are also used to produce volume modules: fiberglass laminates, CLT cross-laminated wood panels, steel frame structure, glued wood frame structure and, above all, light wooden frame (Perkowski, 2022). Regardless of the material used for production, two methods of building modules are used:

- Platform method – where the wall panels are placed on the lower ceiling and usually covered with the upper ceiling – the modules are then lifted from the bottom, most often using belt slings.
- Balloon method – in which wall panels are attached to the sides of the ceilings – then the modules are lifted using handles attached to the upper part of the walls.

Another category of modular houses are buildings assembled from SIP panels (Structural Insulated Panels) (Yang et al., 2018). Buildings of this type are constructed using wooden or steel frame technology, and the filling consists of structural boards composed of wood-based cover boards, e.g. OSB boards filled with insulation made of polyurethane foam, styrofoam or mineral wool. The house is assembled by the construction team from many prefabricated components delivered by truck to the construction site. Compared to houses built from block modules, the number of components assembled on site is much greater, which causes problems during their assembly. This type of structure may also be affected by weather conditions already at the time of installation, which often requires the construction of temporary protective structures. The time spent on the construction site when assembling this house takes much longer than the finishing work performed in the case of a block module. A comparative analysis of prefabricated house structures: panel (Project A-SIP) and block (Project B-MOD) was conducted by D. Lopez and T.M. Froese (Lopez & Froese, 2016). For both cases, the construction costs per square meter of building area were determined, the assembly and finishing time was compared, and the advantages and disadvantages important for making the decision to choose one of these two methods of building a modular house were noted. The cost analysis showed that, excluding the costs of purchasing land, preparing the plot and foundations, the actual production and assembly costs were 11% lower in the case of building houses from block modules. However, it was decided that the cost difference was not large enough to exclude other quality factors when choosing the construction method.

A significant advantage of the panel construction method compared to the modular construction method is their easy transport. Due to the flat shape and low weight of the panels, they can be stacked and adjusted to each other. However, in the case of block modules, only one or a maximum of two modules can be transported on a car. The main advantage of the modular construction method compared to the panel construction method is the quality of production control. The modules are entirely manufactured in-house, which allows for a more thorough quality control system. In the case of a panel construction, the SIP panels themselves are the only element produced in the production hall, and other elements such as board sheathing, furniture, devices and installations are made on site, which involves quality control problems.

In practice, modular houses are most often implemented in frame technology based on the assumption of the so-called open prefabrication, in which a significant part of the work takes place on the construction site and includes the installation of internal cladding and external insulation (Krause, 2015). This category includes the so-called Canadian houses in which the building frame is made of single prefabricated wooden elements and the walls are made of structural or plasterboard boards. Modular house solutions based on a steel frame are also becoming more and more common, in which, after installing the structure made of steel profiles, finishing elements and insulation are installed in a similar way to wooden modular houses.

A new material for building modular houses are prefabricated expanded clay concrete elements. Expanded concrete is an excellent material for building modular houses because it is light and at the same time resistant to external factors. Thanks to the low heat transfer coefficient of this material, expanded clay houses are warm and energy-efficient.

2. Modular construction in Poland

Due to the change in construction law regulations, which now allows the construction of buildings with an area of up to 70 m^2 without the need to obtain a building permit, year-round modular houses are an increasingly popular alternative to traditional construction in Poland.

Currently, in Poland, mainly modular houses with a wooden frame are designed and built, e.g. Simple House, BXB studio, Moduo Fabryka Domów (Rybarczyk, 2022). These are systems of prefabricated panels of various sizes which, thanks to frame technology, can be easily connected to each other. Modular buildings are offered in several variants, both for a single-story house and for a version with an attic. For example, in the system of modular units designed by BXB studio, 18 modules made of KVH construction wood and CLT cross-laminated wood can be used to obtain 5 different residential units with different variants (Matysiak, 2022).

As part of the research project "Energy and process-efficient construction" financed by the National Center for Research and Development from European Funds – Intelligent Development Program, work was also started on the implementation of the production of block modules fully finished and equipped with installations, joinery, kitchen furniture and bathroom equipment. Complete prefabricated elements prepared in modular technology can be used to build both single-family buildings and large multi-family buildings (Tofiluk, 2022).

3. Proposed classification of modular houses

Sulik and Zawiślak made an attempt to systematize the technology of construction of buildings made in a prefabrication plant in relation to the construction method (Sulik & Zawiślak, 2021). The following categories of construction performed in

a prefabrication plant include: 1D prefabrication – single prefabricated elements, 2D prefabrication – panel system, 3D prefabrication – modular construction. 1D prefabrication in practice means the use of prefabricated foundations, columns, reinforced concrete and steel beams. 2D prefabrication, also known as the panel system, includes not only reinforced concrete elements, but also ready-made walls, ceilings and roof truss elements with a wooden or steel structure. In the case of 3D prefabrication defined as modular construction, in addition to wooden and steel structures, the "other" group is also specified, which includes mixed and composite systems (Tofiluk, 2022).

The classification constructed in this way does not take into account forms of modular construction carried out using frame technology, which uses prefabricated 1D wooden elements and SIP panel systems used to assemble modular houses. Based on a literature analysis of the issues related to the construction of modular houses, the authors present in Figure 1 an attempt to classify modular houses depending on the type of prefabricated elements and assembly technology, materials used and method of use.

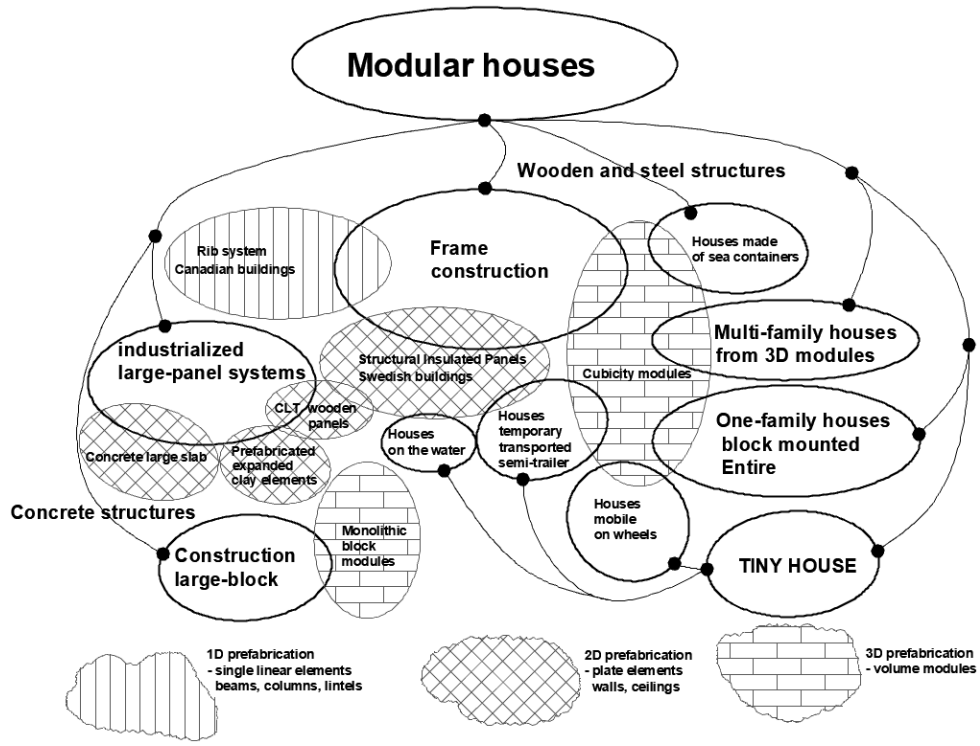

Fig. 1. Classify modular houses (*own research*)

This classification excludes construction solutions combining traditional and prefabricated methods and hybrid technologies using selected features of the types mentioned above (e.g. panel construction with prefabricated three-dimensional bathroom modules).

4. Ecology and energy efficiency of modular house technology

The measure of direct and indirect greenhouse gas emissions caused by a specific operation of a facility throughout its life cycle, converted into CO_2 mass equivalent, is the so-called carbon footprint. The carbon footprint is estimated according to life cycle assessment (LCA) procedure described in the PN-EN 15978:2012 standard – Sustainable construction facilities. Assessment of the environmental performance of buildings Calculation method. According to of this standard, the carbon footprint included in the slogan "Global warming potential" is divided into:

- built-in – originating primarily from built-in building materials and activities related to renovation and demolition of the building;
- operational – resulting from the amount of energy consumed by the house.

In the case of modular houses built using prefabricated technology, the environmental benefits result primarily from lower energy consumption during construction and operation and from increased tightness of buildings compared to traditional solutions. Lower energy consumption during construction results from performing production processes in factory conditions. Reducing the working time on the construction site allows you to reduce the energy consumption needed for the operation of equipment, as well as to choose more ecological energy sources, which may be impossible on the construction site itself (Lawson & Ogden, 2022; Płoszaj-Mazurek, 2022).

As a result of the controlled production of modular houses, the consumption of raw materials and semi-finished products is optimized, and the generated waste is easier to reuse or dispose of. Modular buildings are largely adapted to be moved to a new place or used in the construction of other facilities, which is an important step towards a circular economy.

In the works of Płoszaj-Mazurek and Lawson and Ogden showed that the impact of modular construction on the environment is on average 40% lower than that of traditional construction (Lawson & Ogden, 2022; Płoszaj-Mazurek, 2022). Light wooden frame technologies used in modular construction are less expensive than forms of reinforced concrete prefabrication, and they also help reduce the consumption of concrete and reinforcing steel in foundations, because the weight of the finished structure is only 20-25% of the weight of a traditional brick building.

5. Innovation in modular building solutions

Modular construction introduces innovative solutions and technologies that increase the comfort and functionality of homes. Figure 2 shows an example of residential modules that can be used to shape homes for seniors in any way.

Modern technology of production and assembly of modular houses naturally involves the introduction of innovative passive heating systems and intelligent management of energy consumed at home (Szuba, 2013).

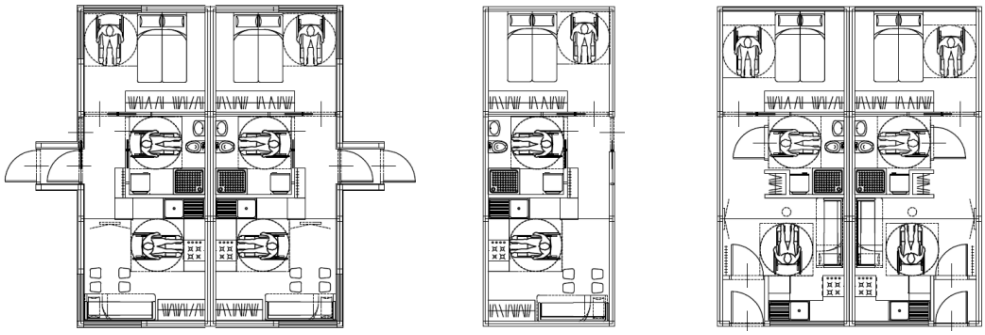

Fig. 2. Modules of a residential building for seniors (*own research by B. Szuba*)

Heating system solutions are used based on the installation of photovoltaic panels on the roof of the house, installation of heat pumps and recuperators. The specificity of the construction of panel and spatial modules, which requires the use of thin external walls, means that the modular building has innovative solutions for panel-ing and insulation layers in order to meet thermal and acoustic requirements and fire safety.

Conclusions

The construction of modular houses is one of the most dynamically developing trends in sustainable construction. The use of modular construction technology translates into measurable benefits for the natural environment. Prefabrication reduces the consumption of natural resources, and buildings created this way have a lower carbon footprint than those built traditionally. The built-in carbon footprint is reduced mainly by lower consumption of building materials, and the operational one – by the high quality of workmanship that characterizes modern prefabrication technology. The advantage of transferring most of the works to the prefabrication plant was to reduce the inconvenience of building houses on people and the sur-roundings and to limit the duration of the investment only to assembly works in the field. The low weight of the modular house structure also reduces the need to strengthen the foundations or structures of added buildings. The assembly of modular houses is carried out in a dry system, which practically makes it possible to perform it in all weather conditions.

Building modules and prefabricated elements are manufactured in factory con-ditions, which minimizes the possibility of manufacturing errors and ensures high quality of individual components.

In order to accelerate the development of modular house construction technology, it is recommended to introduce uniform design standards. Companies operating in Poland producing modular houses according to: own technology, they usually carry out the entire investment themselves, from the design phase to their construction on the investor's plot. The authors of this publication intend to work on developing

a catalogue of wall, ceiling and other structural elements of modular houses, which would specify standard solutions for connecting these elements. Such a catalogue would contribute to the development of this technology in Poland and would be a useful tool for architects and designers of modular house structures.

Bibliography

Bonds, D.J. & Bramwell, E.P. (2002) Modular building frame. U.S. Patent vol. 297, no. 8 October.

Ganiron, T.U. & Almarwae, M. (2014) Prefabricated technology in a modular house. *International Journal of Advanced Science and Technology*, 73, 51-74.

Generalova, E.M., Generalova, V.P. & Kuznetsovaa, A. (2016) Modular buildings in modern construction. *Procedia Engineering*, 153, 167-172.

Krause, P. (2015) Energooszczędne budynki w technologii lekkiego szkieletu drewnianego. *Builder* 19, 6, 90-85.

Lawson, R.M. & Ogden, R.M. (2010) *Sustainability and Process Benefits of Modular Construction*. HE CIB World Building Congress, The Lowry, Salford, United Kingdom.

Liang, N. & Mengxuan Y. (2021) Research on design optimization of prefabricated residential houses based on BIM technology. *Scientific Programming*, 2021(10).

Lopez, D. & Froese, T.M. (2016) Analysis of costs and benefits of panelized and modular prefabricated homes. *Procedia Engineering*, 145, 1291-1297.

Matysiak, K. (2022) Prefabrykacja w budownictwie jednorodzinnym. *Z:A Zawód Architekt*, 87, 17-25.

Perkowski, T. (2022) Modułowe budynki wielorodzinne. *Z:A Zawód Architekt*, 87, 26-38.

Płoszaj-Mazurek, M. (2022) Prefabrykacja w architekturze zrównoważonej. *Z:A Zawód Architekt*, 87, 54-60.

Rybarczyk, T. (2022) Prefabrykacja dziś i jutro. *Z:A Zawód Architekt*, 87, 74-76.

Sulik, P. & Zawiślak, Ł. (2021) Budownictwo modułowe jako nowoczesna technologia prefabrykacji. *Inżynier Budownictwa*, 12, 56-61.

Szuba, B. (2023) A thermo-circulating heating structure utilizing air circulation to heat architectural objects. *Construction of Optimized Energy Potential*, 12, 1, 51-62, DOI: 10.17512/bozpe.2023.12.06.

Szulc, J. & Sieczkowski, J. (2020) Budownictwo modułowe – zastosowanie, zalety, rodzaje systemów. *Inżynier Budownictwa*, 5, 82-86.

Tofiluk, A. (2022) Forma budynków modułowych. *Z:A Zawód Architekt*, 87, 44-52.

Wyrzykowski, A. (2019) Tiny houses czyli projektowanie (nie)minimalistyczne. *Przestrzeń, Ekonomia, Społeczeństwo*, 15/l, 85-106.

Yang, L., Huajie, W., Hongliang Q., Yanxiang, L. & Qiao, E. (2018) Effect of autoclaved lightweight concrete panels on the mechanical performance of container building and its equivalent method. *Advances in Structural Engineering*, 7, 21.