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Advantages and Disadvantages of Modular Construction, including Environmental Impacts

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Abstract. Similar to other fields, the construction industry tends to constantly evolve. There is an increasing demand for the construction of new buildings regarding the speed of the construction process, economy, and minimization of the negative effects on the environment, i.e. sustainability. These requirements can be met by using prefabrication for this construction. Modular construction represents one of the prefabrication technologies that is becoming increasingly popular worldwide. The topic of this article is the use of modular construction, even from the sustainability point of view. There is a basic overview of modular construction, its history in the construction field, an overview of the materials used, and the possibilities of its implementation. Furthermore, this article provides an overview of the advantages and disadvantages of modular construction. The advantages are listed in terms of quality, economy, time, and ecology as well as in terms of construction flexibility and work safety, both during production and assembly on the construction site. The disadvantages of modular construction discussed in this article are the complicated transportation of modules, demanding coordination of production and construction, the requirement for detailed construction planning, and the non-acceptance of this construction technology by the general, and sometimes professional public. This article also deals with the comparison of modular construction technology with conventional construction technologies. It points out the possibility of reusing materials from disassembled modular buildings. It also points out the ways to control and mitigate the impact of modular construction on the environment throughout the life cycle of modular building. Only after a thorough analysis of these aspects of modular construction, is it possible to explore other ways to further increase the efficiency of this technology in all directions and also to make even better use of its environmental impact minimization potential.

1. Introduction

The construction industry tends to constantly evolve like other fields. Requirements for the construction process, with respect to its speed, efficiency, and minimizing the negative impacts on the environment, can be successfully addressed by prefabricated structures. Modular construction is one of the technologies of prefabricated structures. The topic of this paper is modular construction use with regards to sustainable construction.

In the field of building construction, construction techniques can be divided into four basic categories according to the structure, namely: masonry structures, reinforced concrete monolithic structures, prefabricated structures, and their combinations. Prefabricated structures are increasingly used in the construction sector in relation to the growing effort for higher construction efficiency. One of the currently used construction technologies with a very high degree of prefabrication is so-called modular construction. Modular construction in this case falls into the category of prefabricated structures.

Prefabrication is the process of mass producing building components in specialized plants at a site other than the future assembly site, and transporting the building components or already assembled components to the construction site. A modular structure can be defined as a construction system that is created by assembling several modules together into the desired shape while the module represents a dimensionally unified spatial unit (segment). These units are manufactured off-site in special plants and are transported to the construction site, where they are assembled in a complete structure. Depending on the builder's requirements for the building size and function, the structure may consist of one or more modules. The term **"Permanent Modular Construction**" (hereinafter **PMC**) is also used for modular construction. A frequently used term in connection with modular construction is so-called "volumetric modular construction". It is a subset of a modular structure, the process of assembling completely closed prefabricated modules together, either side by side or with several floors, in order to create the final structure. Other types of modules include, for example, double-sided or partially double-sided modules, corner support modules, and non-load-bearing modules [1-4].

In general, building modules are made of a single material or a combination of several (usually up to three) primary building materials, namely wood, steel, and concrete. Each material used has its advantages and disadvantages. For example, modular structures with a wooden frame are light, easy to transport, and have good thermal insulation properties. In contrast, steel and concrete modules have a longer service life, allow greater design flexibility, and are more fire-resistant. The appropriate composition and material used for the module depend on the purpose of use and requirements for the construction. However, for reasons of efficiency and specialization, most manufacturers focus on the production of modules from a single material [5].

Modular construction technology can be used for structures whatever the character of the use. Modular construction is suitable for permanent, long-term, and temporary structures, due to the possible relocation of entire modules. PMC can also be used effectively in areas where natural disasters occurred, or regularly occur. At present, this construction technology is developed at such a level that the resulting structures meet all the requirements of standards, such as requirements for thermal and sound insulation, fire resistance, etc. It is therefore comparable to other conventional technologies in terms of housing quality.

2. Current state and development of modular construction

Besides the companies that are engaged in the implementation and modular structure construction and that have developed detailed production documents for their needs, other experts are currently dealing with this construction technology. For example, K. SUBRAMANYA et al. in their research identified and analysed the main advantages and disadvantages of modular construction and compared them with conventional construction technologies, based on a thorough analysis of the existing scientific literature dealing with this topic. W. FERDOUS et al. focused on modular construction development and its mechanical properties in their research. They point out the advantages and disadvantages of the wooden sandwich elements used. Furthermore, they bring an evaluation of the suitability of the main materials used with respect to the construction of high-rise modular buildings. An evaluation of the speed of construction was also carried out. The research found that the modular construction implementation time in the construction industry seems to be slower than expected due to the complex coordination of the project. It points out the need for more intensive logistical support and training, as well as the need to make modular construction more popular [6-11].

New approaches to the management and implementation of construction projects using BIM are increasingly being used both in the European Union and elsewhere in the world. Using BIM in the construction of public works contracts is already mandatory or will soon be mandatory in many countries. This certainly applies to modular construction as well. It was proved in the article by H. QIN and Y. YAO. They present the differences between PMC and general prefabrication from different perspectives, especially in terms of the BIM (Building information modelling) implementation impact, the main factors influencing the use and impact on construction efficiency, and the scheduling perspective, in their study. The most common types of completed structures are also listed here. The main positive factors of both technologies and their comparison are analysed in the study based on the collected data. M. LEE et al. in their study propose a relational matrix of key activities and tasks of BIM modular construction projects for the BIM practical task analysis in Korea. The designed matrix can serve as an auxiliary tool in deciding whether it is worth using BIM when designing a particular type of modular structure. This matrix use can help plan the BIM use in practice [12], [13].

3. Modular construction advantages

The next part of this paper summarizes and evaluates the advantages and disadvantages of modular construction and divides them into individual subchapters.

3.1 Qualitative aspect

The production process is limited only by climatic conditions thanks to the transfer of most of the production process indoors. Thus, the risk of building material and product damage due to climatic conditions is minimized. Furthermore, module production is more "comfortable" for workers in the indoor environment, and thus "human errors" are reduced, i.e. the quality of the structure and the entire building is increased.

Full digitization and production automation as well as the introduction of an effective system of quality checks of individual phases of module production results in achieving the so-called “line quality” of the products. Each factory worker has his/her own specific work and he/she increases his/her skill and thus the quality of his/her work by frequent work repetition. Modular construction companies have the motivation to introduce Industry 4.0 to achieve such quality and efficiency. It should also be stated that modular construction with the correct design, production process, and quality control can meet all the requirements arising from the relevant local, state, and national regulations, in the same way as the constructions implemented by other construction technologies. These are, for example, requirements for interior acoustics, thermal insulation, interior lighting, etc. For this reason, PMC is also suitable for residential buildings. Structured insulated panels which are airtight and provide excellent thermal insulation are often used to provide PMC thermal insulation. These panels create a light but durable combination of a panel board and closed-cell insulating foam made of polyurethane or expanded polystyrene [14].

Already in the module design phase, the fact that the individual parts of the building are exposed to the risk of mechanical damage during complex transport and assembly by heavy mechanization is taken into account. The modules are thus designed to have high mechanical resistance in order to minimize this risk. This prevents damage during transport and assembly, as well as during the use phase.

3.2 Economic aspect

The Construction Industry Institute (CII) states that the total construction costs are 10–25% lower compared to conventional technologies when the PMC is implemented. Several factors that are listed below also contribute to lower costs [15].

The high construction speed and low requirements for space and construction site equipment result in a reduction of potential costs, e.g. for the necessary occupation of land outside the builder's ownership during construction, construction site equipment in general, and traffic engineering measures that need to be provided in connection with construction. Furthermore, due to the construction speed, the total time worked by workers is lower, so the finances set aside for their wages and possible accommodation are also lower. From the point of view of off-site transport, it is necessary to transport individual modules to the construction site. Thus, there is no need for a constant supply of building materials for construction, which results in a reduction in vehicle fuel consumption together with the reduction in fuel cost. In general, there is an overall reduction in overhead costs.

Line production also means product price control. There is no room for additional work emergence, etc. As a result, the price set when awarding the contract is also the final price. The recycling of material both in the module production and in their disposal represents another aspect for reducing production costs. However, this aspect is further discussed below in the context of the environmental aspect. There are also lower costs for complex construction machinery, such as lifting mechanisms, etc. A lifting mechanism is needed for the PMC installation on the site, however, usually only for the time of its use, and thanks to the short assembly time, the time of its presence on the construction site is significantly lower, so is the lower lease price and operation and maintenance costs. Moreover, a higher construction speed also means a faster return on investment from an economic point of view [16-18].

3.3 Flexibility
Modular construction is able to respond to the current needs or financial capabilities of the owner and it can be expanded or modules removed. This possibility is quite advantageous especially for young families, where both their financial capabilities and the need for additional living space increase over time. On the contrary, it is possible to remove containers from the building and thus reduce its usable area when needed. This can bring a solution to young families how to reach a mortgage, which at the beginning of the construction may not be as high as when building a house with the classic technology, where the space for future offspring has to be designed in advance. The removed modules can then be reused for the needs of another structure. Another possibility is to adapt only the layout of the structure while maintaining the existing usable area or to relocate the structure as a whole. This provides the opportunity to change the overall purpose of the building use, e.g. changing the school building to an administrative building, etc.

Furthermore, it provides great flexibility from an architectural point of view. The resulting structure may not look like an ordinary cube at all. The architectural design is quite variable. High variability can be seen both in stacking modules on each other and in external surface treatment. The structure can also have a sloping roof or a half-span roof, etc. The visitor to this building does not necessarily recognize a PMC structure at all. Modules can also be used to perform high-rise structures. For example, the tallest modular building in the world is the first high-rise modular apartment building "461 Dean" in Brooklyn, New York with 32 floors and a height of 109 m [19].

3.4 Safety
It is well known that the number of fatalities and accidents that result in serious injuries is significantly higher in the construction industry than in all other occupational sectors. This is due to the character of work on a construction site which involves activities that endanger the safety of workers. It is stated that more than 20% of the total number of fatal accidents occur in the construction sector. The main causes of fatal accidents in the construction industry are falls from a height or into depth, crushing by a machine or load, and electric shock. O. KLAKEGG states in his article that there are on average 80% fewer accidents in PMC than in conventional construction. PMC is therefore safer because most work takes place indoors and the duration of work on a construction site, where the risk of accidents is

high, is significantly shorter. It is mainly based on the assumption that work in plants is significantly safer than work on construction sites. P. BECKER et al. conducted a survey based on questionnaires, which showed that 50% of the PMC experts surveyed believe that PMC is safer than conventional construction technologies [20-23].

3.5 Ecological aspect
From an ecological point of view, the benefits of PMC can be in a simplified way divided into benefits related to waste production and the construction process impact on the building environment. PMC generates less waste than conventional structures. Repeatability of production gives the manufacturers an overview of how much material is needed for a given task. R. M. LAWSON et al. found that using PMC can achieve up to 70% reduction in waste production. Another reason for lower waste production is the so-called circulation design, where all buildings are designed so that all their used components and materials can be reused in new structures. Waste recycling therefore takes place internally. PMC is, therefore, a sufficient solution to the need for waste reduction [24-26].

Due to the speed of assembly, the time for which the surroundings of the construction site are affected by increased noise and vibrations from the construction activity is reduced also in the assembly phase. Furthermore, PMC does not affect the surroundings of the construction site with increased dust or greenhouse gas production. As already mentioned in connection with the economic aspect, PMC eliminates the need for a constant supply of building materials to the construction site, and thus the reduction of vehicle fuel consumption results in the reduction in air pollution from vehicle operation [27].

3.6 Time aspect
The large number of PMC advantages, which were mentioned in the previous text, results from the short time of its production and assembly. These include a quick return on finances, a reduction in some overheads, ancillary costs, and staff costs. Fast and operative construction brings a number of advantages. Some of them have already been mentioned above. Its use in crisis situations, natural disasters, and humanitarian operations where immediate assistance is needed, can serve as another example.

This short construction time is mainly due to the relocation of most work to the interior of the plant, where the production process is not limited by adverse climatic conditions, and due to production automation, digitization, and work repeatability. Furthermore, thanks to line production, several activities can be performed simultaneously. It is possible, for example, to produce walls, ceilings, and roofs at the same time and then, in the plant, combine them into one unit, which is then transported to the construction site. As a result, the time required to complete a PMC construction is usually 40% shorter than building using conventional construction methods. The PMC production time in the plant and the assembly time on the construction site range from about 1 day to 4 months. This time mainly depends on the scope and complexity of the construction [6].

4. Modular construction disadvantages

4.1 Complicated transport of modules
It is necessary to transport complete modules with floor plan dimensions of 6 × 3 m or 9 × 3 m to the construction site. Sometimes even larger components are transported, which means dealing with oversized transport. In such a case, it is necessary to obtain special permits and arrange accompanying vehicles, which increases the PMC costs. However, the modules could be manufactured in even larger dimensions resulting in even more complicated transport. It can be concluded that the module dimensions are limited by their transportation possibilities. The transport of PMC components needs to be thoroughly logistically planned. It is necessary to choose such a route from the plant to the construction site where there are no restrictions in terms of passability, such as underpasses, tunnels,

and bends or low power lines, which would prevent transport due to their parameters. Complicated transport also often delays the module delivery to the construction site, which brings along additional costs and a more complicated construction process. Transport constraints on modular construction, therefore, represent obstacles to the PMC timeliness and cost-effectiveness. Furthermore, it is necessary to provide the module transport from the vehicle to the place of assembly by means of a lifting mechanism, most often a mobile crane. This process carries a high safety risk.

4.2 Harmonising coordination and the requirement for accurate planning
Due to the difference between PMC design and conventional technology construction design, more complicated construction process coordination arises. In addition, the planning process is particularly demanding due to the complex components that must be manufactured and assembled during the prefabrication process. For each construction project, perfect coordination during the designing, production, and assembly process phases, including the transition from one phase to the next, represents key elements for both timely completion and required profit. Accurate project scheduling is another requirement. In order to fulfil these requirements, the presence of experts with the necessary experience and PMC knowledge is necessary for the work teams. However, there is a lack of such experts, which brings a significant limitation for this method of implementation. It is very important for designing the PMC to be carried out by designers who are specialists in this type of construction or are at least sufficiently aware of it. If the PMC design is carried out by a designer who does not have the necessary knowledge of this technology, it is likely that the benefits of modularity will not be fully exploited and its use will therefore lose its merits due to inappropriate design. This problem may not only be caused by poor design, but also by inappropriate requirements of the investor, who also does not have sufficient knowledge about PMC, and require the incorporation of elements that are not suitable for PMC into the structure [28], [29].

4.3 Occasional reluctance to PMC acceptance.
Some individuals still refuse to recognize PMC as a full-fledged structure, despite the fact that nowadays PMC can be designed and manufactured to meet all standard requirements in the same way as structures made by conventional technology. Furthermore, some users, and even experts, are unable to approve PMC from an aesthetic and architectural point of view. The fact is that some financial institutions also have this opinion, which may make it impossible for a potential builder to obtain a mortgage. This issue is caused both by some territorial regulations and psychological factors. Low and insufficient information level is another aspect that makes it necessary to make the lay and professional public aware of this issue.

4.4 Initial costs of establishing the production plant.
Although the costs of manufacturing and assembling PMC are lower than when using conventional technology, it is necessary to build a production plant. In areas where labour costs and other requirements for conventional construction are lower than the PMC production plant establishment, the use of conventional technology is more financially advantageous for the specific construction. However, in the case of establishing a production plant, a return on the money invested is expected [30].

5. Modular construction in terms of environmental impacts
Nowadays, companies are under constant high pressure for sustainable development in all areas of industrial production. M. LANDMAN defines sustainable structures in general as "the design and implementation of a structure using resource-efficient methods and materials that do not threaten the environment or the health and well-being of the structure occupants, construction workers, the public or future generations". Improving construction sustainability, i.e. reducing the economic, environmental, and social impacts of the construction, represents one of the basic requirements of modern construction activity. One possible solution may be building prefabrication implementation.

For example, R. M. LAWSON et al. found out that PMC can reduce the amount of waste deposited in landfills by 70%, the operation of means of transport for material by up to 70%, and the production of increased noise from the construction site to its surroundings by 30-50% compared to conventional technologies [25], [31].

5.1 Waste management related to PMC

The amount of waste generated by conventional construction methods has always been an environmental challenge. Waste production during construction activity has a high impact on the environment. It is stated that construction production generates 30-40% of waste production [32].

One of the means to minimize waste is the so-called circulation design. The principle of circulatory design is the design of structures, their components, and materials in such a way that they can be reused. These components and materials from the liquidated structure are therefore recycled and used for further module production. This can be denominated as internal material recycling. This fact significantly supports the principle of circular economy and thus prolongs the product life cycle and minimizes waste production, and thus leads to more careful and efficient resource use. However, in order to achieve a circular construction process, it is necessary to consider the material and individual component future recycling already in the design phase of the construction.

One of the means that can increase circulatory design efficiency is the use of BIM technology and intelligent assets. CH. TURNER et al. propose to use sensors for this purpose, which would be implemented in modules already in the plant and would record structure data. These sensors would transmit information about the modules and would be used at all structure life stages. During the structure liquidation phase, they would provide the workers with detailed information about the individual components of the module and instructions on the correct disassembly and recycling of the material [33].

Furthermore, PMC generally minimizes the waste generated, thanks to production repeatability. Manufacturers have an overview of how much material is needed for a given job. Another advantage of waste management is that PMC has a greater potential for waste management compared to conventional methods, even within a construction site [34].

6. Results and discussion

One of the main reasons why the advantages discussed in this article are linked to modular construction is the relocation of a large part of the production to the interior of production halls. Then it is possible to apply repeatability, automation, and digitization of the production process, which results in its efficiency both in terms of time and money. Shortening the construction time means reducing the construction financing costs. Due to the relocation of large parts of the production to the interior, the time of affecting the surroundings of the construction site with increased noise is reduced, the safety risks of workers are reduced and it is possible to provide higher product quality. The reduction of negative environmental impacts, reduction in waste production, internal recycling, and circular design implementation, and thus achieving a circular economy, adds another advantage.

However, modular construction also has its disadvantages, which can negatively affect both its efficiency and increase financial costs. These disadvantages include the complicated module transport to the construction site, the occasional reluctance to accept modular construction, the complex coordination, and the requirement for accurate planning associated with lack of available skilled workers. Another finding is the positive impact of modular construction on the environment in connection with production and generated waste recycling. One way how to achieve efficient waste management, recycling, and circular construction process is to use BIM together with smart assets.

7. Conclusions

In conclusion, modular construction generally has more advantages than disadvantages. Identified disadvantages can be eliminated on the basis of further research and further development of this technology. However, it is not possible to say in general that the use of modular construction would always be more appropriate than the use of conventional construction technology, due to the fact that each construction is individual and unique in a way, and therefore the choice of construction technology is not always a straightforward and easy matter. This choice should include a thorough decision-making process and evaluation in the construction design phase, not on the basis of the general advantages and disadvantages of construction technologies, but on suitability for the specific construction and construction site.

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