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Impact of Module Arrangement on Loads, Structure, and Functionality in a Wooden Modular House

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Abstract

Prefabricated structures play a significant role in modern construction due to the numerous benefits that positively impact the efficiency and quality of works and their sustainable development. Thanks to the constantly developing prefabrication sector, we can obtain more and more complex elements of buildings that would be impossible to make directly on the construction site. In the case of even such complex elements, their quality and precision of workmanship are at such a high level that it reduces the risk of any construction problems in the future.

The article presents a literature review on the history of wood and prefabrication, with a particular emphasis on the role of wooden modular construction in the scientific community. The review discusses studies related to construction efficiency, sustainability, and innovative design and technological solutions. In the subsequent part of the study, three single-family modular house models were designed using a previously calculated standard module as a base element. These buildings were composed of combinations of three or four modules. However, the analysis revealed that such constructions could not bear all the assumed loads. In response, individual optimisations were introduced to tailor the designs to specific requirements. This process involved modifying cross-sections, adding additional structural elements, and implementing extra supports, enabling the structures to meet the requirements of ultimate limit states (ULS) and serviceability limit states (SLS).

The research demonstrates that creating a universal module capable of fulfilling both ULS and SLS requirements in every configuration while maintaining structural optimisation is highly challenging. The results provide a significant contribution to the development of modular construction research. They offer valuable insights into the design process and enable the effective adaptation of modular units to specific configurations and project requirements in the construction industry.

Key words: timber buildings; modular construction; timber structures; prefabrication; innovative design solutions.

1. Introduction

Wood is one of the first forms of building material known to mankind. Initially, tree branches were used to build such primitive forms as huts, but with the development of the ability to process this material, more and more complex structures began to be erected. An example is the Pons Subilicius bridge in Rome, a wooden beam structure built in 625 (1).

The oldest surviving sacral wooden buildings in Europe show how building systems have developed over the centuries, from simple to more complex. The initial religious buildings were based on structures resembling huts with walls made of logs. Reaching the 10th century, the first mentions of the timber frame structure were noticed – the most widespread in Scandinavia (2).

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The first mention of prefabricated houses can be found in 1624, when English ships transported houses made of wood to the colony in Cape Ann. The assembly of this type of house was done very quickly, thanks to the construction of the houses, which consisted of ready-made wall panels (3). The beginning of modular construction is considered to use containers for transporting goods by sea as portable houses. Containers were cheap and easy to transport material. Initially, they were used as technical construction buildings, but over time service or residential houses began to be built (4).

Modular construction, known today, owes its shape to the Scandinavian countries. The first factories that produced prefabricated building elements were established there (5). In 1990, modular timber construction developed rapidly in Europe by introducing cross-laminated timber to the market. As a result, modular houses have become more technologically advanced (6). Currently, there is a growing interest in this form of construction, not only in Scandinavian countries, but also in Germany and Canada. Also, in Poland, the modular construction market grew from PLN 1.9 billion to PLN 4.9 billion per year in 2019-2023 (7). At least several dozen companies are presently erecting modular multi-family houses, also from Poland (8). There was an increase in interest not only from individual investors who decided to build single-family houses, but also from multi-family buildings (9). An example of such a building is the HoHo Vienna building, located in Vienna. It is one of the tallest skyscrapers on earth, measuring 84 meters. It is made of 365 m3 of glulam and 1600 m3 of cross-laminated timber (10).

Modular construction uses prefabricated modules that are prepared in more than 80% off-site and then transported to the investment site. Each module consists of structural, stiffening and thermal insulation elements. Modules are divided according to the material they are made of: concrete, steel, wooden (11,12).

Modular technology is a challenge, but it is also an opportunity for the development of the construction industry. Buildings in this technology are erected much faster than traditional ones. It allows work to be carried out simultaneously on the construction site, such as foundation works, and in the factory (9,13). There are several types of prefabrication. Open, in which the wall structure with sheathing is made in the factory, and the rest of the work is done on the construction site, and full, in which everything is done in the company (14). In paper (15) authors explores the advantages and barriers of modular construction through case studies of projects like Leishenshan Hospital (China), the 2018 Winter Olympics media residence (South Korea), and Global Academy (UK). It highlights modular construction’s benefits in efficiency, cost savings, waste reduction, and eco-friendly design while addressing logistical and technological challenges for its broader application, including its potential for permanent buildings.

Thanks to production in controlled conditions, we ensure much higher quality in executing individual components compared to on-site construction. Each stage of work is supervised and the factory conditions allow for better control of materials (9,16). The technical parameters, sizes and finishing of the modules can be adapted to the designated functions of the building, which means that the projects are each time optimized and adapted to the conditions of the investment (14). This translates significantly into investment costs, as weather conditions and human factors do not affect substantially the construction (9,13). In terms of structural solutions, wooden modular structures base their technology concept on producing steel modules. It is based on the use of simple techniques, e.g. screws or glues. Currently, steel prefabrication has a more extensive network of solutions, which translates into a more willing choice. Transport is one of the important issues considered when designing, resulting from the limitations of transport capacity. The use of the 4D BIM process in modular construction is increasingly being considered. This term means linking the 3D model to the construction schedule. Using such solutions at the design stage can eliminate unnecessary costs, such as reducing more waste (16,17).

There is also increasing interest in modular construction, mainly wooden construction, within the scientific community. A detailed analysis of the evolution of prefabricated and modular timber construction technologies from 1990 to 2023 was shown in the paper by Gutierrez et al. (19). It highlights current trends such as the integration of digital technologies and circular economy approaches. Tenorio et al. (20) examine the modern application of modular timber construction, emphasizing its potential as a sustainable and innovative alternative to traditional materials like concrete and steel. It explores key topics, including the fundamentals of modularity, structural systems, inter-module connections, and the integration of mechanical, electrical, and plumbing (MEP) systems, highlighting timber's versatility and environmental benefits, such as carbon sequestration and reduced ecological footprint.

Reviewing the literature on modular constructions, it can be observed that most works focus on the energy efficiency of such structures and their minimal impact on the natural environment. The article (20) analyses the potential of modular construction to reduce embodied greenhouse gas emissions compared to conventional methods, using California as an example. It identifies 2–22% emission reductions, with results influenced by materials, factory location, and transport logistics, offering a scalable model for other regions. Another paper (21) examines the application of Design for Disassembly (DfD) principles in timber structures, leveraging their modularity and renewability for sustainable construction. It reviews existing studies, highlights significant research areas, and addresses current challenges, offering actionable insights for advancing DfD timber systems in practice and regulation. Meanwhile, study (22) compares the environmental impacts of conventional and modular housing, assessing their sustainability within planetary boundaries across various geographic regions, specifically Australia and Denmark. It finds that modular housing generally has lower environmental impacts, all buildings exceed their allocated share of resources, indicating a need for further reductions in embodied and operational ecological burdens. Another example is paper (23). This study evaluates the energy and daylight efficiency of prefabricated modular units for off-site construction, focusing on their performance across five different climate locations. The results reveal that, while factors like orientation and thermal properties of the building envelope impact energy use, artificial lighting plays a surprisingly significant role in total energy consumption, highlighting the importance of Spatial Daylight Autonomy (sDA) in optimising energy efficiency.

Yet other studies focus on examining the details of walls, floors or connections. In the paper (24) author investigated a new modular wall construction system using Cryptomeria wood (Cryptomeria japonica) through an experimental campaign. It evaluates the mechanical behavior of glued wood connections, load-bearing capacity of modular units, and the impact of an interior corkboard layer, highlighting the system's potential for strength and identifying critical design parameters for safe implementation. This study (25) investigates how cracks in sheathing panels affect the structural performance of modular timber buildings, mainly focusing on the racking stiffness and strength of timber walls. By combining experimental and numerical methods, the research demonstrates how wall geometry, panel shape, and connection types influence crack initiation and propagation.

It is possible can come cross possible to come across articles referring to advanced methods of modelling wooden structures, such as (26), which presents a reconfigurable modular timber grid inspired by traditional East Asian architecture, combining the principles of modularity with Industry 4.0 technologies like robotic milling. The system minimizes material waste through shallow-notched joints and reuses timber components in diverse configurations, promoting sustainability and resource efficiency. It also employs finite element methods to evaluate the structural performance of semirigid joints, integrating design, manufacturing, and recycling into an adaptable construction approach. Another example would be work Bianconi at al. (27), which introduces a mass-customized housing model using cross-laminated timber (CLT), aligned with Industry 4.0 initiatives by the European Union, aimed at innovation in the Architecture, Engineering, and Construction (AEC) sector. It leverages generative models and evolutionary principles to enable intuitive customization during early design stages, providing a decision-support system for designing single-family and emergency homes, particularly in central Italy.

Despite the growing body of research on modular construction, a critical and glaring gap remains in studies focused on the specific modeling and flexibility of modular buildings. While a significant amount of literature discusses various aspects of modular construction, such as environmental impact, sustainability, and design for disassembly, far fewer delve into the critical issue of how modular units can be adapted to different configurations within a building layout. Most existing studies concentrate on the benefits of modular construction and the performance of specific materials, like timber, but they fail to provide a comprehensive analysis of how modular units can be effectively integrated into diverse building designs or whether the same modules can be efficiently utilized across various layouts. This lack of understanding presents a major hurdle in advancing modular construction.

To truly unlock the potential of modular buildings, further research is urgently needed to develop models that address these fundamental challenges. This includes understanding how modular components interact in different spatial arrangements and how these configurations impact structural integrity, energy performance, and cost-effectiveness. Without this critical foundation, the ability to optimize the flexibility, scalability, and overall effectiveness of modular buildings in real-world applications remains severely limited. The gap in research is not just a theoretical issue—it directly hinders the practical application and evolution of modular construction in the built environment.

2. Material and methods

The main structure of the module was designed with dimensions of 9.0x3.8 x 3.3 m. It was constructed using glued laminated timber Gl28h. The structure was loaded according to the design standards currently in force in the European Union. The permanent and live loads of the structure were assumed, as per reference (28), with the following values:

- roof load – 1.57 kN/m^2;
- ceiling load – 0.88 kN/m^2;
- green terrace load – 2.36 kN/m^2;
- external wall loading – 1.90 kN/m^2;
- payload – 2.5 kN/m^2.

Climatic variable loads were adopted following the standards (29,30). The snow load was assumed assuming thw III – rd snow zone in Poland, where the value of the graund snow load is 0.96 kN/m^2. The wind load was calculated assuming the I-st wind zone – and the wind speed of 22 kN/m^2, by the PN-EN 1991-1-4 standard (30).

Then, a model of the structure was created in Autodesk Robot Structural Analysis 2022 (hereinafter: ARSAP), and internal forces in the structure were calculated, determining the necessary dimensions of structural elements. The column cross-section has dimensions of 240x220 [mm], floor beams 120x200 [mm], and cross beams 240x280 [mm]. The bracing was made of φ16 bars made of S275 steel. A single building module with the adopted cross-section dimensions is shown in Fig. 1.

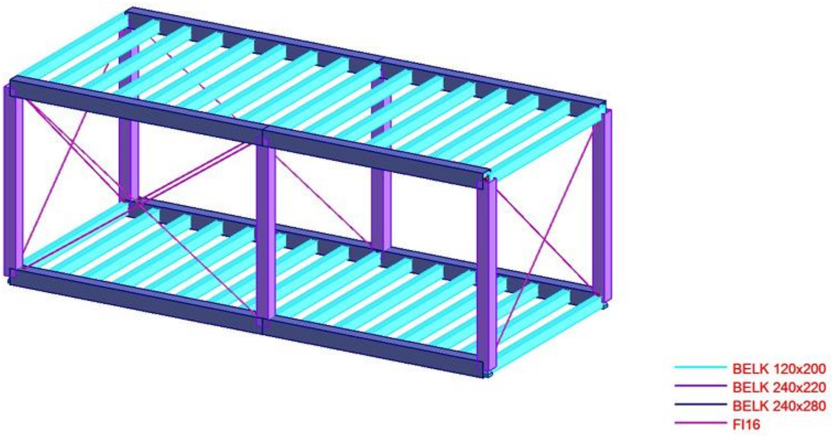


Fig. 1. Single Building Module

The next stage of the work involved creating three models of the building, by combining three or four individual modules. The modules are named respectively – M1, M2 and M3; they are shown in Fig. 2 and 3. Fig. 2 provides an overview of the layout of the modules in the building, while Fig. 3 shows the structures of each module.

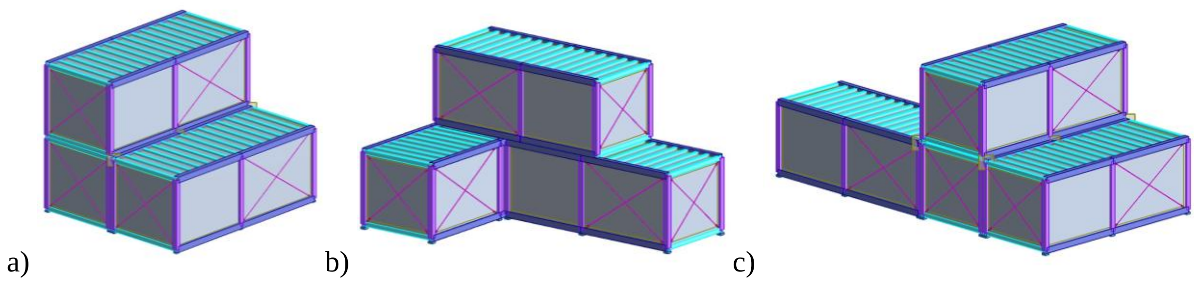
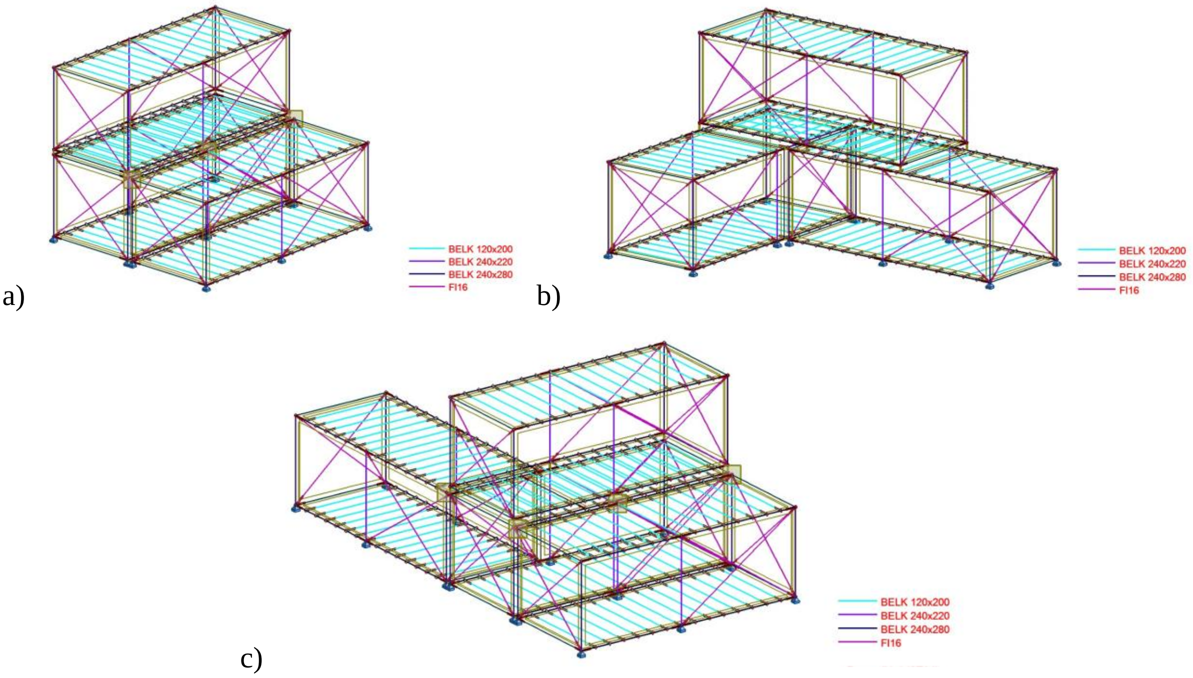

a) b) c)

Fig. 2. Models of the analyzed buildings: a) M1, b) M2, c) M3.



a) b) c)

Fig. 3. Construction of the analyzed models: a) M1, b) M2, c) M3

The modules arranged in buildings M1, M2 and M3 were subjected to the impact resulting from the assumed permanent load – the storey above, snow evenly distributed on the roof surface and wind, which was assumed as a simulation of wind loading available in the ARSAP program. An example of snow loading is shown in Fig. 4, and an example of wind loading for two directions is shown in Fig. 5.

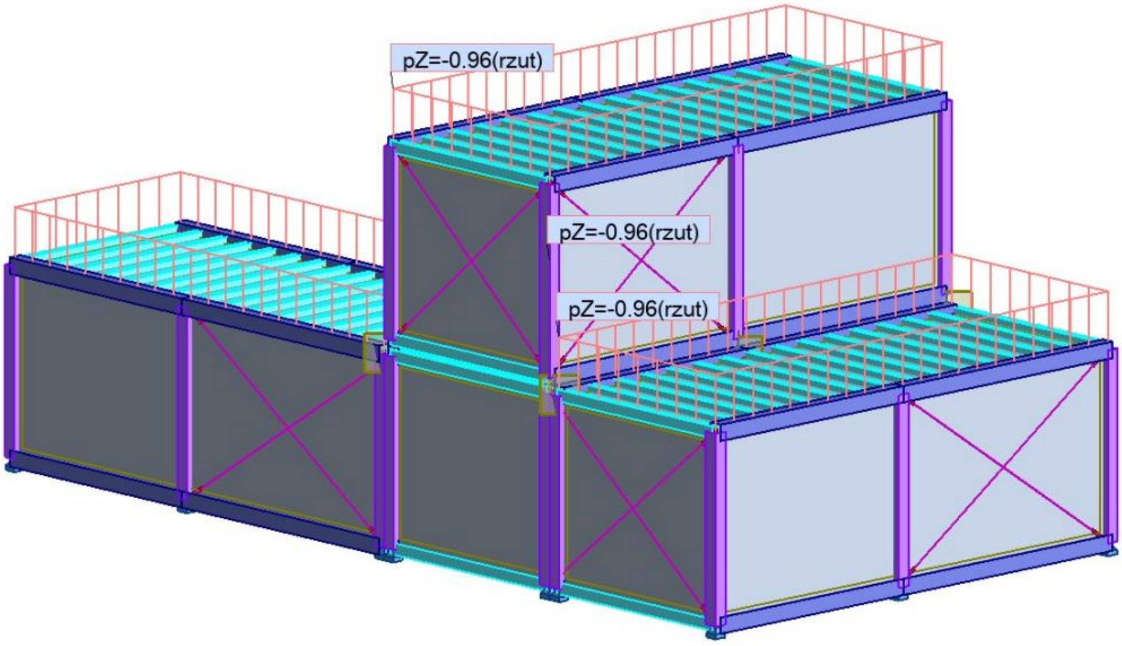


Fig. 4 . Snow Load – Selected Case – Module M3

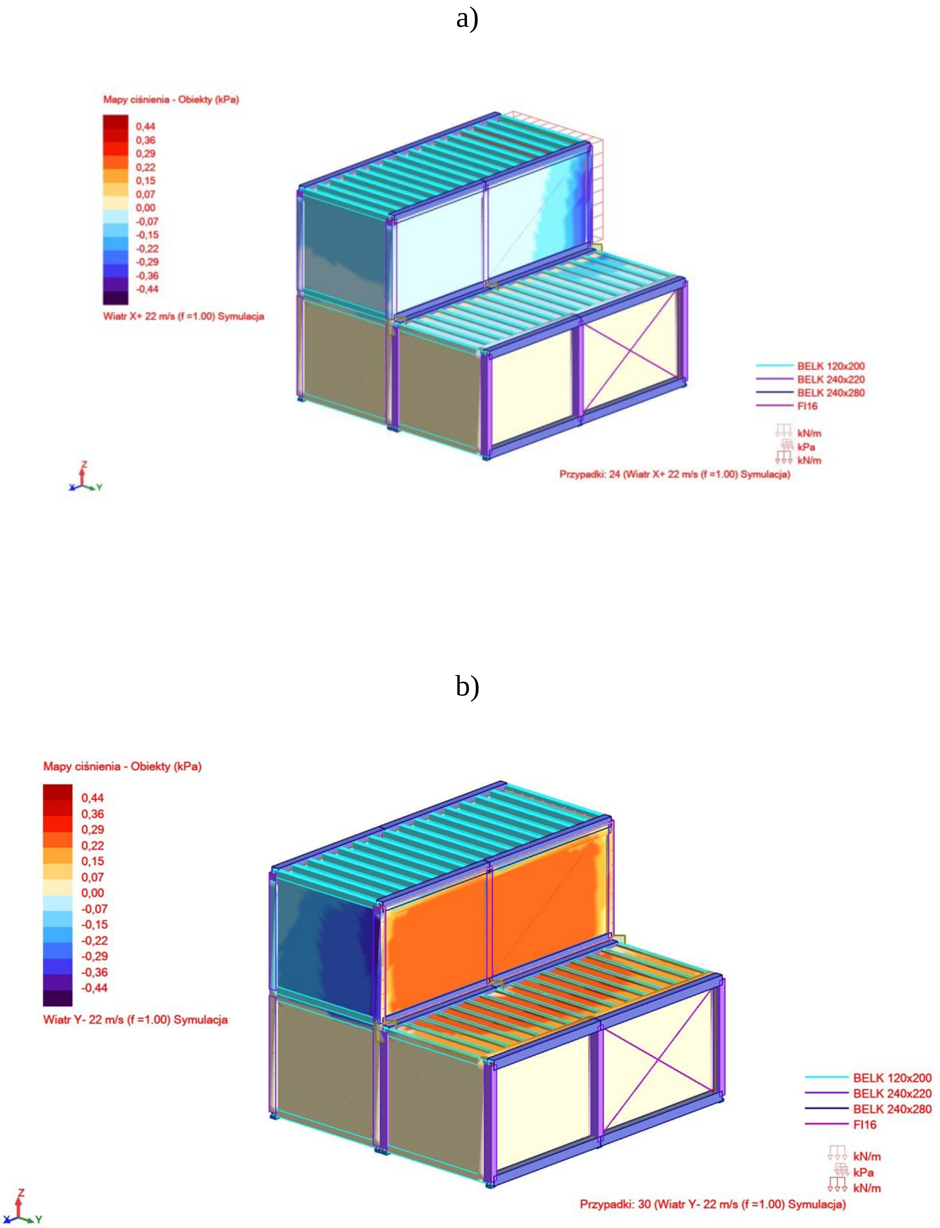


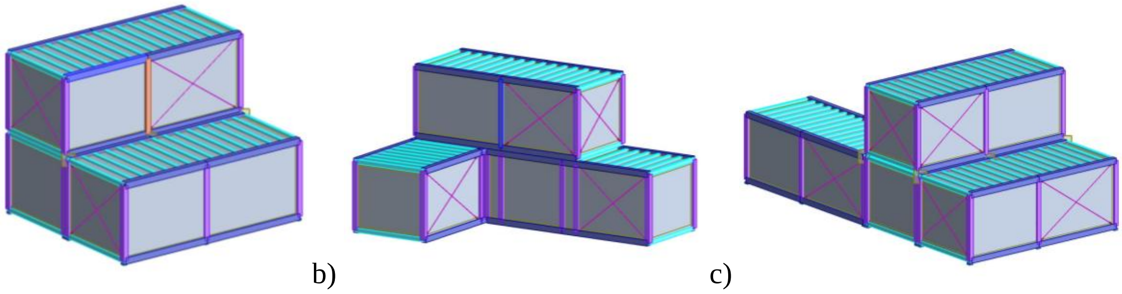
Fig. 5. Example wind load of the M3 module structure: a) wind direction X–, b) wind direction –Y

An automatic load combination was made considering the PN-EN 1990:2004 standard (31). The model's load combination was created based on the given loads, which were previously classified as permanent, variable loads. Appropriate safety factors are applied for each load group. The primary purpose of using a load combination is to find one or more situations that will have the most adverse effect on the structure.

The 1st order analysis was used for the calculations. First-order linear analysis is a computational approach based on the assumption that the response of a structure to the loads applied to it is proportional to them. It is also assumed that the deformations are small and linear, based on which we can adopt some simplifications in the overall analysis.

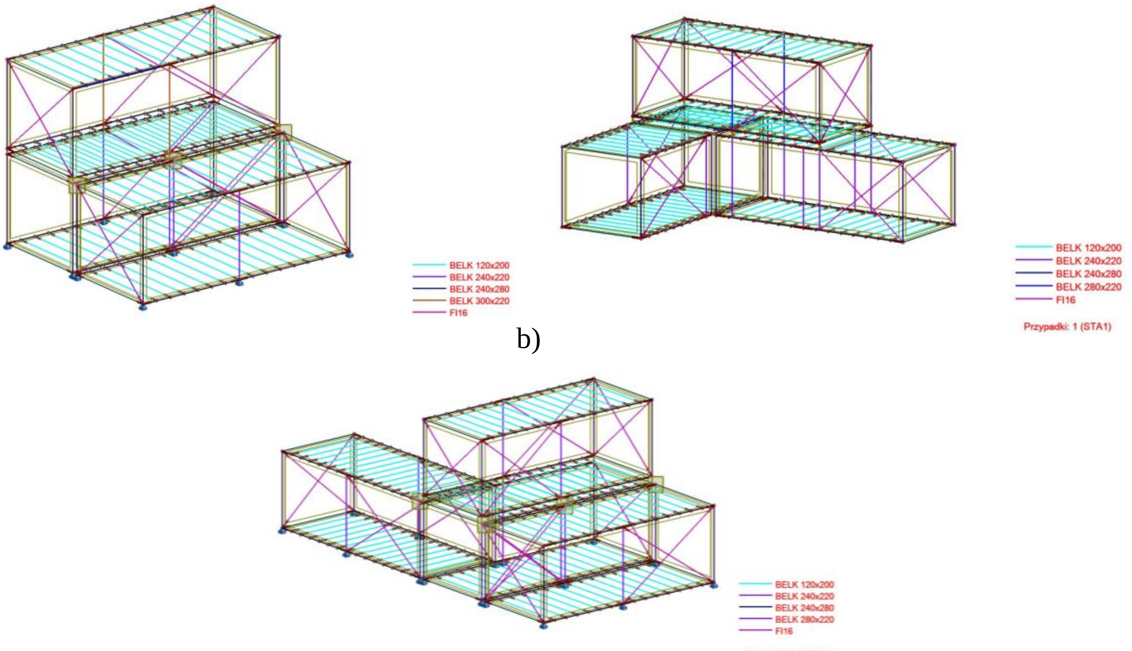
The modules were connected to each other using the rigid connection function available in ARSAP. This function is used to model the components of elastic structures perfectly rigidly. All travel directions and rotation relative to the vertical axis are locked in the nodes.

In the next step, modifications were made to the individual models, as shown in Fig. 6 and 7. Each module located on the top floor has two columns with dimensions of 280x220 [mm] or 300x220 [mm].



a) b) c)

Fig. 6. Models of the analyzed buildings: a) M1, b) M2, c) M3.



a) b)

c)

Fig. 7. Construction of the analyzed models – after modification: a) M1, b) M2, c) M3

In model 2, additional columns were inserted due to the module placed on the 1st floor, the structure of which does not fall out in the axis of the lower columns. Columns were added on the ground floor so that the upper module was supported correctly (Fig. 8, 9). Models 2 and 3 insert an additional column in the bottom concave corner.

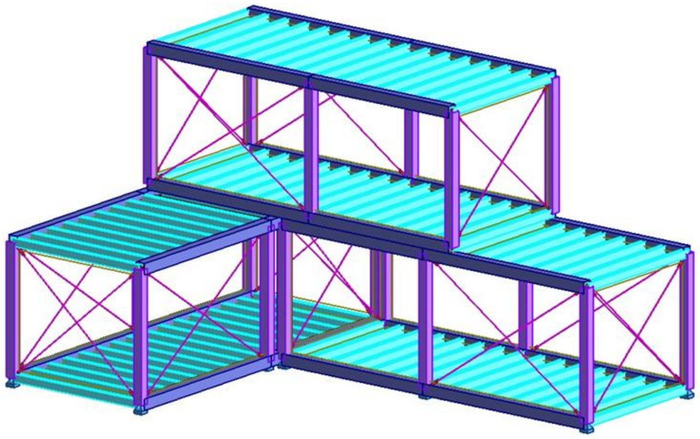


Fig. 8. Model M2 – Standard Layout

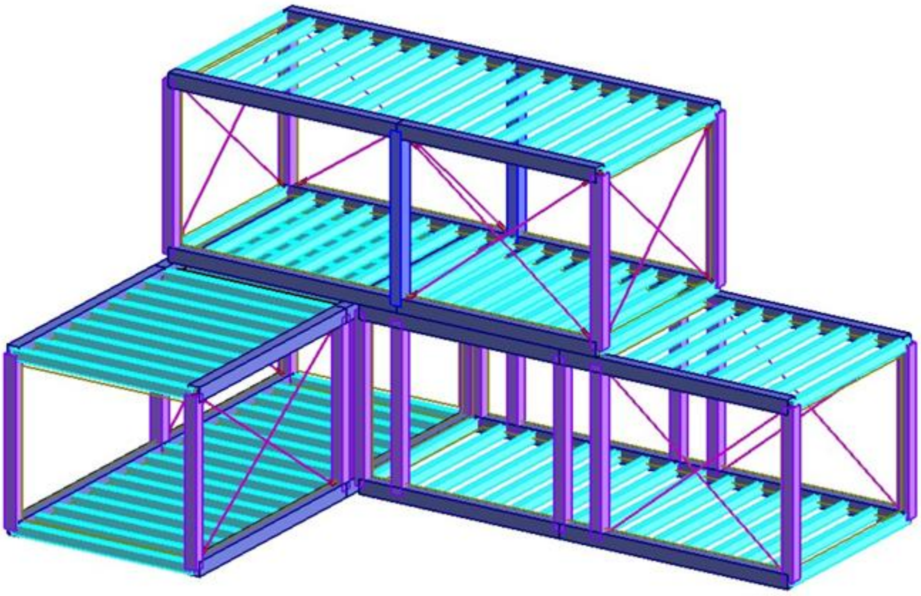


Fig. 9. Model M2 – after optimization

The standard module has braces on two narrow faces and on half of the span of longer walls (Figure 8). Due to the need to place window and door joinery in the model, some bracing was removed so that it did not adversely affect the entire structure (Figure 9). The above compares model 2 with the basic concentration system and after optimization. Thanks to this solution, the building can maintain its functionality.

3. Results

Stage 1 of the results – basic setting of the models

With the help of the ARSAP calculation program, the behavior of the structure under the influence of applied loads was obtained. Below, Table 1, 2 and 3 lists the values of internal forces and displacements for individual models.

Table 1. Maximum Values of Internal Forces for Columns

No	**Number**	**Cross-section**	**Model**	**Fx**	**Fy**	**Fz**	**Mx**	**My**	**Mz**
				[kN]	**[kN]**	**[kN]**	**[kNm]**	**[kNm]**	**[kNm]**
1	62	240x220	M1	98.77	5.88	0.2	0	-0.62	-12.11
2	178	240x220	M1	194.23	0.01	0	0	0	0
3	63	240x220	M1	98.73	-5.71	0.18	0	-0.58	12.61
4	173	240x220	M2	139.71	1.38	0.02	0.03	0	2.31
5	74	240x220	M2	190.17	3.28	0	0	0	-10.65
6	229	240x220	M2	98.57	-5.40	0.28	0.48	-0.77	11.08
7	61	240x220	M3	153.66	1.13	1.49	-0.05	0	2.28
8	63	240x220	M3	238.15	-3.31	0	0	0	6.60
9	171	240x220	M3	91.44	-4.75	-0.32	0	0.98	12.90

Table 2. Maximum Values of Internal Forces for Beams

No	Number	Cross-section	Model	Fx	Fy	Fz	Mx	My	Mz
				[kN]	[kN]	[kN]	[kNm]	[kNm]	[kNm]
1	367	240x280	M1	62.96	-3.69	-31.45	-2.29	39.86	-2.92
2	203	240x280	M1	0	0	27.59	0	37.31	0
3	229	240x280	M1	0.06	-1.45	26.06	0	31.15	1.2
4	176	240X280	M2	-2.17	-0.14	-30.71	-0.03	41.53	-0.08
5	225	240X280	M2	2.7	0.2	-25.03	0.01	29.2	-0.12
6	108	240X280	M2	-2.07	-3	30.5	0	41.25	-0.23
7	167	240X280	M3	-1.84	-0.39	30.5	0	41.25	0.39
8	255	240X280	M3	0.11	0.1	23.44	0	28	0.09
9	9	240X280	M3	23.81	1.85	29.2	4.16	29.2	4.16

Table 3. Maximum Values of Internal Forces for Secondary Beams

No	Number	Cross-section	Model	Fx	Fy	Fz	Mx	My	Mz
				[kN]	[kN]	[kN]	[kNm]	[kNm]	[kNm]
1	148	120x200	M1	-1.39	0.05	-4.47	0	-2.65	0.04
2	215	120X200	M1	2.82	0.02	-8.98	0	-5.74	-0.02
3	221	120X200	M1	-0.83	0.04	8.42	0	8	0.04
4	91	120x200	M2	0.04	0.03	7.78	0	7.91	0.02
5	98	120x200	M2	1.15	0.05	9.48	0	-10.65	-0.05
6	319	120X200	M2	-7.28	0.02	7	0	7.12	-0.01
7	282	120x200	M3	1.15	0.02	8.29	0	-10.88	0.02
8	180	120x200	M3	1.73	0.01	11.02	0	-12.9	0.01
9	154	120X200	M3	-2.15	0.12	8.42	0	8	0.12

Table 4. Maximum Displacement Values for First Module System

No	Node	Instance	Model	Ux [cm]	Uy [cm]	Uz [cm]	Rx [rad]	Ry [rad]	Rz [rad]
1	13	SGU/92	M1	0	2.5	-0.1	-0.004	0	0
2	48	SGU/1	M1	0	0	-1.4	-0.001	0	0
3	65	SGU/60	M1	0	0.4	-0.3	0	-0.004	-0.006
4	326	SGU/12	M2	1.2	-0.1	-1.6	0.001	0.003	-0.001
5	330	SGU/20	M2	1	-2.4	-1.5	0.004	0.003	-0.001
6	112	SGU/59	M2	0	0.5	-2.7	-0.001	-0.002	-0.002
7	327	SGU/46	M3	2	0.1	0	0	0.004	0
8	167	SGU/2	M3	0	2.5	-0.1	-0.005	0	0
9	193	SGU/2	M3	0	0.4	-0.3	0	-0.004	-0.006

Table 4 shows the maximum displacement values for all models. It shows that not every serviceability limit state has been met. The values of displacements that exceeded the SLS are marked in red.

Table 5. Structural Element Efforts in Models Before Optimization

No	Element	Cross-section	Model	Maximum strain
1	Column	240x220	M1	0.14
2	Beam	240x280	M1	0.29
3	Secondary beam	120x200	M1	0.34
4	Column	240x220	M2	0.20
5	Beam	240x280	M2	1.27
6	Secondary beam	120x200	M2	0.31
7	Column	240x220	M3	0.31
8	Beam	240x280	M3	0.29
9	Secondary beam	120x200	M3	0.35

Above are tables containing the values of the strength of the structure elements before optimization. It follows that in M2, the effort in the beam exceeded the permissible value; in other cases, the condition was met. Such a basic module will not transfer loads, so modifications must be made. The results of such a procedure are presented in step 2 of the results.

Stage 2 of results

The results for the models are summarized below. The forces were compared with the distinction between individual components of the structure. Table 6,7,8 shows the maximum internal forces and displacements for modified models.

Table 6. Maximum Values of Internal Forces for Columns – After Modification

No	Number	Cross-section	Model	Fx	Fy	Fz	Mx	My	Mz
				[kN]	[kN]	[kN]	[kNm]	[kNm]	[kNm]
1	170	240x220	M1	137.09	-1.04	-0.11	0	0.37	-3.43
2	63	300x220	M1	99.06	-5.67	0.22	0	-0.72	12.83
3	61	240x220	M1	68.78	3.44	-1.73	-0.02	-1.51	5.2
4	173	240x220	M2	139	1.31	0.04	0.04	0	-2.24
5	228	280x220	M2	92.32	4.74	0.9	0.41	-0.96	-11.52
6	64	240x220	M2	56.86	-1.78	-0.03	0	-0.04	-2.96
7	61	240x220	M3	147.14	1.22	-1.51	-0.3	0.05	2.33
8	63	240x220	M3	233.74	-3.12	-2.64	-0.24	-4.36	6.38
9	171	280x220	M3	92.11	-4.6	-0.35	-0.06	1.1	13.05

Table 7. Maximum Values of Internal Forces for Beams – After Modification

No	Number	Cross-section	Model	Fx	Fy	Fz	Mx	My	Mz
				[kN]	[kN]	[kN]	[kNm]	[kNm]	[kNm]
1	367	240x280	M1	-31.62	-2.33	39.86	-4.73	39.86	-4.73
2	203	240x280	M1	0	0	27.59	0	37.31	0
3	229	240x280	M1	-0.15	1.89	26.06	0	31.14	1.16
4	176	240X280	M2	-4.02	-0.14	30.71	-0.04	41.53	-0.08
5	225	240X280	M2	-6.26	0.28	-24.98	0.02	29.10	-0.17
6	108	240X280	M2	1.42	-0.3	30.5	0	41.25	-0.234
7	167	240X280	M3	-1.78	0.38	30.5	0	41.25	0.39
8	255	240X280	M3	0.11	0.1	23.44	0	28.00	-0.1
9	9	240X280	M3	18.13	6.79	-23.84	1.84	29.20	4.07

Table 8. Maximum Values of Internal Forces for Secondary Beams – After Modification

No	Number	Cross-section	Model	Fx	Fy	Fz	Mx	My	Mz
				[kN]	[kN]	[kN]	[kNm]	[kNm]	[kNm]
1	215	120x200	M1	2.75	0.04	-9.02	-0.03	-5.9	-0.14
2	215	120X200	M1	2.35	0.04	8.42	0	8	0.04
3	148	120X200	M1	-2.49	0.05	-4.51	0.03	-2.74	-0.14
4	91	120x200	M2	0.08	0.03	7.78	0	7.91	0.02
5	98	120x200	M2	1.12	0.05	-9.02	0	-9.52	-0.05
6	319	120X200	M2	-6.56	0.02	0	0	7.12	-0.01
7	282	120x200	M3	1.15	0.02	8.29	0	-10.88	0.02
8	180	120x200	M3	1.73	-0.02	11.02	0	-13.05	-0.06
9	154	120X200	M3	-2.04	0.12	8.42	0	8	0.12

Table 9 shows the maximum displacement values for all models. It shows that none of the serviceability limit states has been exceeded.

Table 9. Maximum values of displacements for the first system of modules – global extremes after modification

No	Node	Instance	Model	Ux	Uy	Uz	Rx	Ry	Rz
				[cm]	[cm]	[cm]	[rad]	[rad]	[rad]
1	13	SGU/92	M1	0	2.1	-0.1	-0.004	0	0
2	231	SGU/70	M1	0.6	-0.1	-0.5	0.001	-0.003	0.001
3	65	SGU/60	M1	0	0.4	-0.3	0.001	-0.004	-0.005
4	330	SGU/2	M2	0	-2	-0.1	0.003	0	-0.001
5	341	SGU/15	M2	0	-0.2	-1.6	0.001	-0.001	0.001
6	324	SGU/87	M2	0	0	-0.5	-0.009	0.001	0
7	327	SGU/48	M3	2	0	0	0	0.004	0
8	167	SGU/5	M3	0	2.1	-0.1	-0.004	0	0
9	379	SGU/1	M3	-0.3	0	0	0	0	0.005

Tables 6,7,8 present the maximum values of internal forces, which show that the greatest forces and moments occur in columns in M3, in beams in M1. In secondary beams, the greatest forces occur in M1, while the moments occur in M3. M2 generally has average force and torque scores, possibly due to the additional reinforcement in the lower storey.

Below are tables containing the values of the strength of the structure elements after optimization. The most stressed columns are in Model 3, and the secondary beams are in M2.

Table 10. Structural Element Efforts in Models After Optimization

No	Element	Cross-section	Model	Maximum Strain
1	Column	240x220	M1	0.10
2	Beam	240x280	M1	0.29
3	Secondary beam	120x200	M1	0.34
4	Column	240x220	M2	0.20
5	Beam	240x280	M2	0.79
6	Secondary beam	120x200	M2	0.46
7	Column	240x220	M3	0.29
8	Beam	240x280	M3	0.29
9	Secondary beam	120x200	M3	0.35

Calculation models M1, M2, M3, made in ARSAP are available for inspection after sending information to the authors.

2. Discussion

Although a single model was initially designed, individual optimisation had to be made for the needs of a given facility and adapted to the particular situation. Modular construction can be described as something repetitive, done several times. However, each time the designer must remember that each situation is different and requires different adjustments. Sometimes this requires the use of an additional column, reinforcement, and other times the removal of a structural element. It follows that the designer cannot design a single universal module that will serve in every case.

Proper module arrangement in a wooden house significantly affects its use and functionality. You can easily adjust the layout of the rooms to your individual needs. For example, an open space can be created consisting of several modules or divided into zones, including one module for the day room and the rest for the night part.

The optimal solution is to arrange the modules in the axis, otherwise it is necessary to use additional reinforcements in the form of columns.

4. Conclusions

Based on the analysis, the following conclusions can be drawn:

1. The forces and moments obtained from the calculation models before optimization are within the ULS condition.
2. The values of internal forces obtained in the case of the first-order analysis, in the models after optimization, in each case, meet the ULS condition.
3. The values of displacements and deflections obtained in the calculation models before optimization were not met in every case, which results in not meeting the SGU condition.
4. All values of displacements and deflections in the calculation models after optimization have been met each time, i.e. the SGU condition has been met.

5. In models 2 and 3, before optimization, there is an instability of the nodes in the RY direction in the concave corner. During the modification, a column and a restraint were inserted, which resulted in the leveling of instability.
6. The concentrations were modified due to the door and window joinery in each calculation model during optimization. In model 2, additional columns were inserted on the ground floor to provide support for the upper floor. Also in each model, two cross-sections of columns on the top floor were enlarged to prevent excessive displacement.
7. Comparing the models before and after optimization, the effort of the elements of the structure before the modification was not met in M2, while after that, all values are less than acceptable.

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