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Innovations in architectural education in terms of mobile and prefabricated structures

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ABSTRACT: Sustainability and the impact of built environment on ecology are key issues in contemporary architecture. Modular architecture and prefabricated light structures represent a very good area for experimentation, especially for finding innovative solutions to contemporary architectural problems. These types of structures should be particularly explored in architectural education, which requires a continuous pursuit of new solutions. The main aim of this article is to provide empirical evidence that working with such structures helps students to master innovative architectural solutions. First, is presented a case study involving several projects, where an experimental approach to modular architecture design has been implemented. Second, the authors report on a survey carried out among architecture students to gauge their perceptions on the importance of the applied educational tools in the successful accomplishment of their projects. The survey results confirm that sustainability and ecology are crucial issues in contemporary architecture, and that modular architecture and light structures enabled students to discover and implement solutions leading to a high positive impact on the environment.

Keywords: Innovations in education of architecture, mobile structures, prefabricated architecture, modular structures

INTRODUCTION

Complementary adaptation to bioclimatic conditions is a critical trajectory of contemporary architectural design. To achieve this adaptation, energy-integrated building design is applied [1]. Life cycle assessment is an integral part of this method. Key stages of life cycle assessment are associated with, among others, the construction phase, material manufacturing that follows the precepts of sustainable development, and the building's demolition phase. To shorten each stage of building design, innovative structural and material solutions are implemented on an increasingly large scale. These include prefabricated structures which are often used in modular buildings. According to Chau et al, the construction sector is responsible for almost 40% of the world's energy consumption, 30% of global resource consumption, it produces 25% of the world's solid waste, its share in global water consumption is 25%, 12% in land use, and it produces 33% of the world's greenhouse gases [2].

This analysis shows the severe impact that the construction sector exerts on the global environment and the necessity to design based on sustainable development tools and an energy-efficient standard. To summarise, sustainability and the impact of built environment on ecology are crucial issues in contemporary architecture, and it is vital to focus on reducing land use by introducing alternative solutions based on mobile structures. Currently, several research works have been undertaken in relation to sustainable development, environmentally friendly, and pro-ecological solutions in the context of architectural education [3-6].

In this context, the question arises of how can architectural education respond to the requirements of current and future bioclimatic conditions? It appears necessary to search for innovative design solutions already at the early stages of architectural education, which requires a creative learning space open to iterations and substantive support at every stage of design and theoretical study. A case in point is the Faculty of Architecture at Wrocław University of Science and Technology (FA-WUST) in Poland, where the academic staff conduct teaching in a design studio involving an extensive use of mobile and prefabricated structures. They also supervise Bachelor and Master's degree projects based on an exploration of innovative structural and material solutions that go beyond the traditionally understood architecture.

The authors of this article present an empirical study on this studio to demonstrate that modular architecture and prefabricated light structures represent an area perfectly suitable for experimentation, especially for finding innovative solutions to contemporary architectural problems. These types of structures should be, therefore, widely used in architectural education, which requires an incessant search for novel solutions. The assumption argued for in this study is that working with such structures allows students to achieve a major education goal: mastering innovative architectural solutions by applying them to concrete projects within the modular architecture approach.

PREFABRICATED AND MODULAR STRUCTURES

In construction, prefabricated structures are a trajectory to pro-environmental and energy-efficient design based on the precepts of sustainability. Prefabricated building elements are generated as a result of optimisation and iterative design based on cyclical testing and prototyping. Optimisation is necessary to improve a building's environmental efficiency [7]. Introducing repetitive, system-based elements has increased the efficiency of constructing buildings and has greatly contributed to the application of modular architecture. The concept of modular architecture has been known since the beginnings of building construction. It appeared in numerous conceptual solutions, going back to the first nomadic housing structures, etc. However, its large-scale application came in the second half of the 20th Century.

The Modular Building Institute (MBI) was founded in 1983. The Institute is an association of producers, contractors and resellers in two trade segments: permanent modular construction and relocatable buildings. MBI defines modular buildings as *…An off-site project delivery method used to construct code-compliant buildings in a quality-controlled setting in less time and with less materials waste*. Furthermore, modular design can result in 95% of construction work being performed off-site [8]. The modular architecture is used in a broad range of buildings, from small relocatable structures located in terrestrial and aquatics environments to large housing and public or commercial buildings.

The idea of prefabrication is not new. In the 1960s, residential buildings from large concrete prefabricated panels were being erected on a large scale in Poland. The first document to standardise solutions based on, among other aspects, concrete prefabricated elements, was the BN-74/8812-01 trade standard, approved in 1978. The work of the Construction Technology Institute collected in the years 1950-2016, includes over 800 publications on prefabrication in construction, 400 of which are catalogues of Polish system-based elements that saw use throughout the entire country [9].

The modular and prefabricated architecture is a contemporary trajectory in building design. Component multiplication is crucial in such solutions, allowing for the complete setup of each of a module's segments off-site. Modular design allows for an empirical and experimental approach to the process of designing a building. The modular construction industry, due to its global reach and demand for new buildings while offering short completion times, requires reliable preparation already at the level of architectural and construction education. It becomes necessary to implement elements based on modular solutions, including prefabricated ones, both in architectural theory and practical knowledge. A key trajectory for innovative teaching methods could be the potential to enhance the practical knowledge with inventive creation workshops featuring the preparation of spatial mock-ups based on student projects. Mock-up preparation would provide experimental work with construction materials and an iterative design approach based on a multiplication of modules, allowing for several enhancements to their components.

ARCHITECTURAL EDUCATION AND THE DESIGN STUDIO

The application of innovative solutions in architectural education should be based on a holistic approach to design and process programming. A holistic architectural design theory was formulated and propagated by, among others, Christopher Alexander. He argued that there are certain universal laws that can be observed in the structure of a city or building, as well as in their fundamental unit - the dwelling [10].

While applying innovative solutions in the process of educating architecture students, the holistic approach should be referred to a number of educational levels; namely,

1) the simultaneous introduction of theoretical and empirical knowledge;
2) applying innovative structural and material solutions at the level of theoretical (lecture, seminar) and practical knowledge (design, inventive creation workshop);
3) interdisciplinary co-operation in design, architecture, structural engineering, environmental engineering, installations solutions, the landscape and interiors;
4) applying the building information modelling (BIM) software in the process of modelling architectural elements and structural solutions.

This is the main approach adopted in the design studio which includes first- and second-level degree studies. The principal idea behind this studio is that mobile architecture is an impulse for introducing experimental solutions and for exploring atypical and light modular structural systems, including prefabricated ones. It is also possible to implement energy-efficient solutions and design functional solutions based on minimising usable floor area. To attain these goals, the design studio simultaneously introduced theoretical and empirical knowledge about sustainability precepts, the impact of construction on ecology and varied types of educational tools.

More specifically, the sustainability precepts targeted were the following:

1) public order: demographic change, public health, social integration, education, access to the employment market, public safety, sustainable consumption models;
2) economic order: economic growth, employment, innovation, transport, sustainable production models;

3) environmental order: climate change, energy, air protection, marine ecosystems, fresh water resources, land use, biodiversity, waste management;
4) institutional and political order: global partnership, a policy of cohesion and effectiveness, openness and participation, civic activity.

The impact on ecology refers to strategic actions and efforts to engage in design activities intended to improve the quality of the existing environment, while minimally interfering with the site as encountered. Finally, the educational tools targeted were the following:

1) carrying out urban and contextual analyses;
2) investigating the area's material accessibility and potential;
3) performing iterative 3D studies on virtual and physical models (mock-ups of the units);
4) adopting an experimental approach to designing structural solutions.

The studio ended with a project, for which students had to apply the theoretical and practical knowledge acquired during the lectures and seminars. All the projects implemented an experimental approach to design and involved the use of interdisciplinary concepts and knowledge: architecture, structural engineering, environmental engineering, installations solutions, landscape and interiors. Moreover, students were trained to master four educational tools and to identify four sustainability precepts, as well as to assess the importance of the impact of architectural structures on ecology. Finally, to carry out these projects students used the BIM software for modelling the architectural elements and the structural solutions.

CASE STUDY: A SELECTION OF REPRESENTATIVE PROJECTS

Among the projects carried out by students under the supervision of the authors during the years 2016-2021, the following Bachelor and Master's degree projects were chosen as representative of the following criteria:

1) the implementation of sustainability precepts;
2) the achievement of a high impact on ecology;
3) the use of the targeted educational tools.

Project 1: Micro House (Julia Śliwka, 2020/2021 Academic Year)

Design idea: the subject of this project was a residential module with a total usable floor area of no more than 25 m^2. The building's design allows for locating it in a wide range of conditions. It could be placed both in developed and undeveloped areas. The building was designed for two professionally active persons. The building is to be self-sufficient in terms of energy and to be able to store storm water. The building's dimensions are 4.5 x 5.55 m, with a rhombus-shaped cross-section. Despite its small floor area, the interior space is divided into a rotating zone with a place for rest, work, and sleep, and a permanent section with a kitchen and bathroom (see Figure 1).

Figure 1: Micro house, designed by Julia Śliwka.

Structural and material system: the building was designed to feature a skeletal structural system. The main element of the system are rafters that allow for the desired wall tilt. The dimensions of the rafters are 25 x 15 cm and they are spaced 1.07 m apart. The floor was designed from two types of beams. The first type, which encircles the entire structure, has 30 x 15 cm cross-sections used to support the rafters. The internal beams have 10 x 15 cm cross-sections and form a skeleton that supports the floor layers. The beams used in the structure are recycled. The internal module/movable drum which, when properly rotated, allows for the space to be converted to feature a sofa with a table, a double bed or a dining table, is an essential element of the design. The size of its diameter is affected by the shape of the building, the length of each wall and the structure to which it is attached. This cylinder abuts the interior of the building at three points; namely, two points of the southern wall and the floor. The tilted wall is covered with photovoltaic panels. The kitchen furniture is modular and mobile.

Project 2: Noises. A Modular Resort with a Cyclist Service Area in Józefów, Poland (Joanna Barwińska, 2019/2020)

Design idea: the building under design was located in the Roztocze region. The inspiration for the name (Noises) and the distinctive cascading structure of the building were the sounds made by water when it flows down a series of low stone barrages along the Tanew River. The base design unit was a structural module that can house a variety of uses. Each module was designed as a cube- or cuboid-shaped unit with varied structural dimensions. One of the main functions that affected the design of the buildings was the outline of a bicycle route and its dedicated cyclist service area.

Structural and material system: the building complex was designed at the site of a former quarry within a forest complex, which was intended to supply natural access to materials. Limestone and local wood were used as cladding for façades and floor surfaces. One of the paths to the building's design were energy-efficient solutions. The southern façade was designed to feature photovoltaic panels intended to satisfy the energy demand for heating and air-conditioning in the buildings. The main structural units were six types of cuboid modules with a floor area ranging from 15.9 m^2 to 60.8 m^2. The modules were dedicated to various functions (see Figure 2).

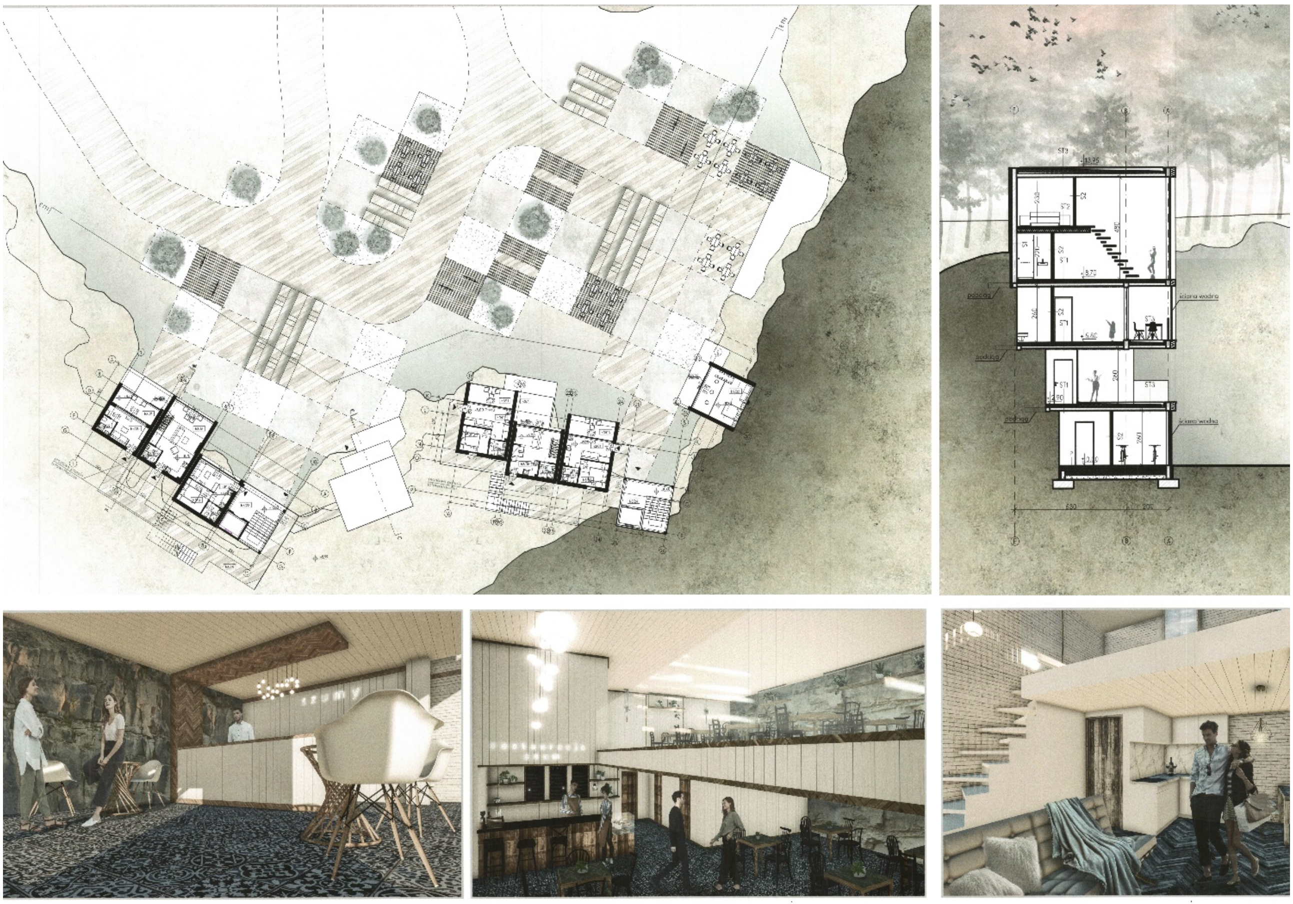

Figure 2: Noises. A modular resort with a cyclist service area in Józefów, Poland, designed by Joanna Barwinska.

Project 3: Floating Mobile Detached House (Marta Soberka, 2016/2017 Academic Year)

Design idea: the objective of this project was to design a mobile, modular housing structure that could provide its residents with essential living conditions and, via the use of modular extensions, demonstrate how it could be reorganised. Thus, apart from a basic housing version for two persons, an alternative option was designed for larger families. Placing a larger number of these structures in close proximity to one another allowed for the establishment of settlements - *housing marinas* on the water that can alter their shape and character depending on user needs and preferences. It was an attempt at using aquatic environments for habitation and entering into a discussion with traditional solutions used in contemporary architecture. The design also includes numerous technological solutions that support its temporary self-sufficiency in the case of relocating it to an area without connection to basic amenities.

Structural and material system: the skeleton of the entire building consists of a steel structure made from 120-type double-t beams spaced every 2 m. The structure also includes 4 x 4 m modules that can be combined depending on the intended size of the structure. The steel profiles used in the structure are to be made from high-quality structural steel of 280 or 350 class, which is hot-dip galvanised so as to prevent corrosion. Finished steel elements are linked using screws, which ensures ease of assembly, extension and relocation to a different site. It is possible to transport the 4 x 4 m modules and connect them at the construction site. The walls were designed to be made from sandwich panels that consist of an external façade panel, a 4 cm thick aerogel insulation and fibre-cement panels. As the building is a floating object not permanently tied to the ground, its foundation was a custom-designed concrete floater that ensures displacement (see Figure 3).

Figure 3: Floating mobile detached house, designed by Marta Soberka.

SURVEY: MATERIAL AND PARTICIPANTS

In order to assess the students' perspective on whether the design studio allowed them to discover and implement solutions leading to a high positive impact on the environment, a voluntary survey was conducted among students. For the survey, the following research questions were formulated:

1. How important are the sustainability precepts and the ecological impact of constructions for contemporary architecture?
2. How important were the four targeted education tools taught in the design studio to ensure the successfulness of the project?
3. To what extent did the project implement the sustainability precepts and achieve a high positive impact on ecology?
4. How useful is modular architecture and prefabricated lightweight structures to design experimental solutions for contemporary architecture, as well as to discover and implement solutions leading to a high positive impact on the environment?

The survey contained 14 items, distributed as follows: two items regarding the first research question, four items regarding the second, five questions regarding the third and two matching items regarding the fourth research question.
Participants had to respond within a 5-point Likert scale, where 1 means not important/not useful at all/did not take into consideration, and 5 means very important/very useful/to a very high extent.

Participants were 28 students (20 females and eight males), of which, in the 2020/2021 academic year, 10 were in their first year of architecture, five in their second year, two in their third year, seven in their fourth year and four in their fifth year. The survey was prepared and distributed by means of the Qualtrics software. Participants read all the survey items, which appeared in a random manner to avoid having an order effect in the results.

SURVEY: RESULTS

The scores given by students were analysed by means of Friedman's two-way ANOVA by ranks using the SPSS software. This statistical analysis is used to compare two or more quantitative variables in a set of data containing dependent samples in which the measurement scale is ordinal. The null hypothesis of the statistical analysis is that the distributions of the scores given by participants to two or more questions are the same.

The first ANOVA performed investigated the students' evaluation of the importance of taking into account sustainability precepts and the ecological impact of constructions for contemporary architecture. It revealed that, for students, sustainability issues (mean = 4.36, SD = 0.911) and the impact of construction on ecology (mean = 4.64, SD = 0.621) are both highly important, $\chi^2(1) = 2.571$, $p = 0.109$ (Figure 4).

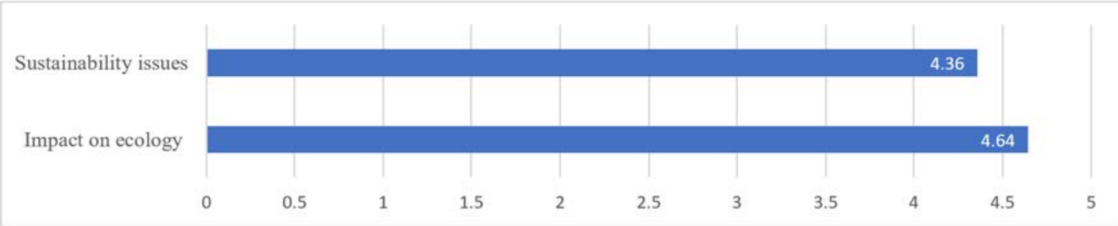

Figure 4: The importance of sustainability issues, and the impact of construction on ecology for contemporary architecture.

The second ANOVA investigated the students' evaluation of the importance of using each of the four educational tools taught in the design studio in the successfulness of their project. It revealed that, for students, carrying out urban and contextual analyses (mean = 3.71, SD = 1.049), adopting an experimental approach (mean = 3.54, SD = 1.347), carrying out an investigation of the area's material accessibility and potential (mean = 3.29, SD = 1.049) and performing iterative 3D studies on virtual and physical models (mean = 3.25, SD = 1.624) are all important, $\chi^2(3) = 5.676$, $p = 0.128$ (Figure 5).

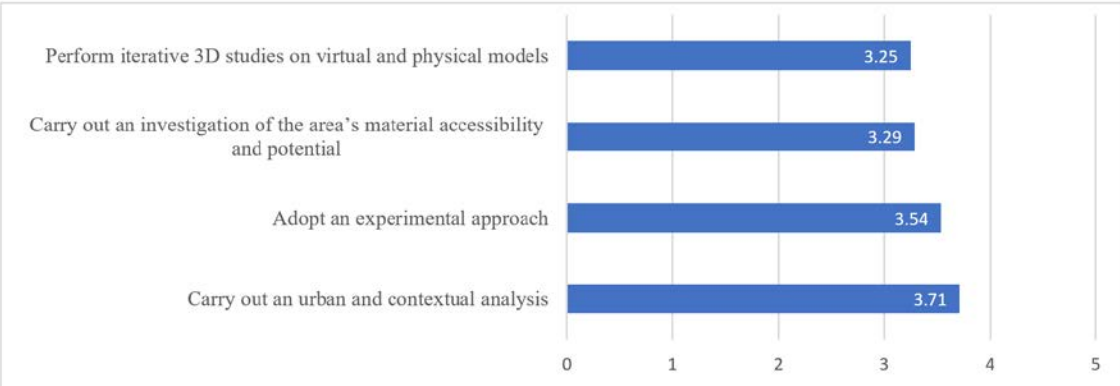

Figure 5: The importance of educational tools to ensure the successfulness of the project.

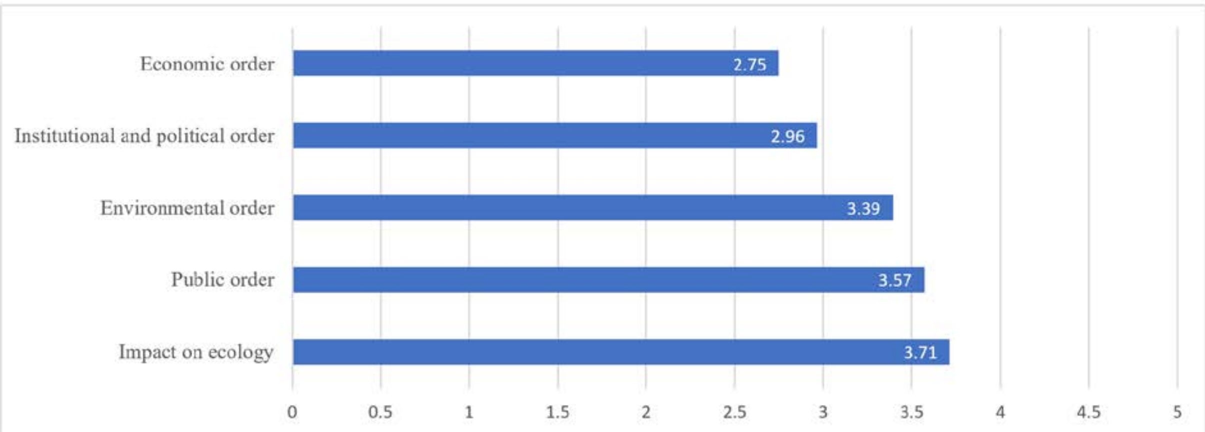

Figure 6: The projects' implementation of sustainability principles and the impact on ecology.

The third ANOVA investigated the students' evaluation of the extent to which their project implemented the four sustainability precepts and took into consideration the impact on ecology of their designed construction. It revealed that the project allowed students to implement public order (mean = 3.57, SD = 1.200) to a statistically significant larger extent than economic order (mean = 2.75, SD = 1.295) and institutional and political order (mean = 2.96, SD = 1.527),

$\chi^2(4) = 16.802$, $p = 0.002$. In addition, it was found that students implemented public order (mean = 3.57, SD = 1.200) to a similar extent as environmental order (mean = 3.29, SD = 1.343) and considered the impact of their constructions on ecology (mean = 3.71, SD = 0.937) (Figure 6).

Moreover, the scores given to the research question about the importance of modular architecture and prefabricated lightweight structures to design experimental solutions for contemporary architecture, were analysed by means of one-sample *chi*-square test. This analysis checked whether the students' scores to this question were significantly different than the scores that would have been randomly given by an automatic system. Finally, the scores given to the question about the usefulness of modular architecture and prefabricated lightweight structures to discover and implement solutions leading to a high positive impact on the environment were also analysed by means of one-sample *chi*-square test.

The first test revealed that students' assessment of modular architecture and prefabricated lightweight structures' importance in designing experimental solutions for contemporary architecture (mean = 4.14, SD = 0.848) is statistically different than a random hypothesised distribution, $\chi^2(3) = 20.857$, $p = 0.000$. Also, the second test revealed that students' assessment of the usefulness of working with modular and prefabricated constructions to discover and implement solutions leading to a high positive impact on the environment (mean = 3.00, SD = 1.277) is statistically different than a random hypothesised distribution, $\chi^2(5) = 19.143$, $p = 0.002$ (Figure 7).

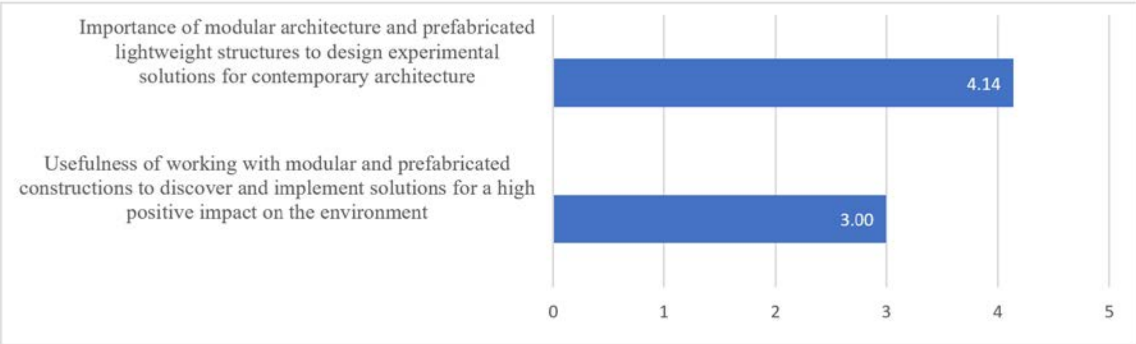

Figure 7: Importance and usefulness of modular architecture and prefabricated constructions.

DISCUSSION AND CONCLUSIONS

The findings of the survey confirm the assertion put forth in this study: modular architecture and prefabricated light structures represent a perfect domain for experimentation, especially for finding innovative solutions in contemporary architecture. Within the rage of five points, the students' responses were affirmative in regard to the importance of modular architecture and prefabricated lightweight structures to design experimental solutions for contemporary architecture, as well as to the usefulness of this method to discover and implement solutions leading to a high positive impact on the environment.

More specifically, in regard to the first aspect, students gave very high scores indicating that in their view, modular architecture and prefabricated lightweight structures constitute a great opportunity for testing novel solutions in contemporary architecture. As for the second aspect, students gave medium high scores indicating that they managed rather well to discover and implement solutions to design construction which have positive impact on the environment.

In the design studio, four educational tools were introduced, and the survey assessed their importance in the successfulness of the students' projects. The survey results indicate that all these educational tools were equally important to successfully carry out the projects. Moreover, the survey also investigated whether students were able to implement, in their projects, sustainability precepts and to achieve a high impact on ecology. The findings indicate that according to students, they were able to implement public order and environmental order to a greater extent than the other sustainability principles.

Finally, students also remarked that their projects took into consideration the impact of their constructions on ecology to a great extent. At a more general level, the presented selection of Bachelor and Master's projects illustrates the intended educational outcomes in terms of the applied educational tools, implementing the precepts of sustainability and ensuring a high positive impact on ecology. As such, this study demonstrates that introducing mobile and light structures in education can enhance architectural awareness and allows for an experimental approach to design problems. Considering the successful outcomes of this approach, it can be concluded that it is an important and proper direction in teaching modern architecture.

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BIOGRAPHIES

Professor Barbara Gronostajska (PhD DSc Eng. Arch.) is an architect and researcher. For 30 years, she has been designing residential architecture. Her main research topics focus on: design for the elderly, universal design, design in the context of health and the modernisation of *large panel*. She is the author of two books, over 100 publications (many included in the Philadelphia List) and a number of architectural designs. She participated in architectural competitions, winning high positions. In 2021, in the Architektura-Murator ranking, her design was ranked 3rd in the category: sustainable and universal design. She is a member of Polish and international organisations, including: the Committee for Architecture of the Polish Academy of Sciences, the Chamber of Architecture, the World Academy of Science, Engineering and Technology; World Institute for Engineering and Technology Education (WIETE), Expert of the Polish National Center for Research and Development, Polish Accreditation Committee (PKA) and the Accreditation Commission of Universities of Technology, Poland (KAUT). She is also involved in social activities: Rotary (in 2014-2015, she was the President of the Rotary-Panorama Club). At her home university, Wrocław University of Science and Technology (WUST), Wrocław, Poland, she has been Dean of the Faculty of Architecture since 2020, a member of the Senate and several University committees. Privately, she is interested in travelling and sports: in winter - skiing - she is an alpine skiing instructor, and in summer - tennis, windsurfing, motorcycle and cycling.

Dr Anna Berbesz (PhD Eng. Arch.) works as a teaching and research assistant in the Faculty of Architecture at Wrocław University of Science and Technology (FA-WUST), Wrocław, Poland. In 2017, she obtained her doctorate in technical sciences in the discipline of architecture and urban planning with distinction for her doctoral dissertation, entitled: *The theme of movement in architecture. Mobile structures temporarily stationed as an alternative attempt to shape architectural objects on the basis of selected examples from the turn of the 20th/21st Century*. Currently, she concentrates her research work on the movement in architecture, in particular, mobile structures stationed temporarily in urbanised and non-urbanised areas, biomimetics and responsive architecture. The result of her involvement in the didactic process are prizes obtained by her students in numerous competitions, including the Pavilosta Poets Huts international competition in Latvia and the International Finsa Award for Architects and Designers. She is the author of numerous articles on the subject of mobile structures, responsive architecture and biomimetics. She is also an active architect specialising in the design of single-family and multi-family houses, adaptation of existing buildings and interior design. Additionally, she co-operates with the industry in the area of co-creating grant applications in the interdisciplinary field.