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B – data collection
C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Lightweight prefabricated floating buildings for shallow inland waters. Design and construction of the floating hotel apartment in Poland

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Abstract

Since the beginning of the 21st century floating buildings have been growing in popularity in Poland. According to market research and quantitative studies, the majority of operative Polish floating buildings serve for commercial purposes, such as short-term rentals, vacation houses and floating marinas. Simultaneously, despite the increasing demand, the development of floating buildings in Poland is limited by the inconsistent legislation, government policy and, most importantly, natural conditions of Polish inland waters. The most attractive sites for floating architecture are the semi-natural lakeshores and riverbanks. At the same time, low water levels and poor maintenance of many Polish basins require special architectural and engineering solutions. The article presents our experience with meeting the market's demand for small cost-effective floating commercial buildings despite the local shortcomings of inland waters on the example of the floating apartment built in 2019 on the Roś Lake in Pisz, Poland. The presented building was intended as a water-based extension of the existing hotel on land. It was designed as a "modern barn" with all-glazed gable wall allowing for a spectacular view to the lake. With a 50 sqm footprint, the one-story house with a mezzanine has a small draft of 33 cm and meets the stability criteria defined for inland waters. The presented case study shows that integrating the naval architecture theory, Building Information Modeling simulation along with cutting-edge construction techniques such as Scottsdale Construction System (SCS) and polyurethane spray insulation, can bring significant progress into the development of the floating buildings market in Poland.

Key words: *Building Information Modeling, floating building, hotel apartments, integrated project delivery, stability simulation, waterfront*

INTRODUCTION

A floating building is usually defined as a stationary floating structure, that is secured in waters and not intended for or usable in navigation [Queensland… 2007; SDCI TIP 3229 2017]. A typical floating building consists of a heavy floating system built in concrete or steel and a habitable lightweight superstructure built in a timber or steel frame technology [FLANAGAN 2003].

Since the beginning of the 21st century floating buildings have been growing in popularity in Poland. According to market research and quantitative studies, the majority of operative Polish floating buildings serve for commercial purposes, such as short-term rentals, vacation houses and floating marinas. Simultaneously, despite the increasing demand, the development of floating buildings in Poland is limited by the inconsistent legislation, government policy and, most importantly, lack of available attractive sites [PIĄTEK 2018].

The problem of the limited number of good locations for floating buildings in Poland comprises two different issues: the local policies and the natural conditions of inland waters [MISZEWSKA-URBAŃSKA 2016]. This paper covers the architectural and engineering solutions to the second aspect of the problem.

Floating hotel apartments are short-term residential buildings that usually take advantage of water proximity to create a unique water-living experience for guests [RIJCKEN 2005]. It means that they are likely to be situated in the natural rural settings rather than in the cities. Therefore, the semi-natural lakeshores and riverbanks, which are very common in Poland due to poor maintenance of waterways, are the most attractive sites for floating architecture. These waters are usually permanently shallow or very variable in terms of depths. The depth at sites suitable for floating buildings, rarely exceeds 1 m. In such conditions, the standard technical solutions for floating houses such as a heavy concrete floating system are very difficult to implement due to their contribution to the building draft.

This paper presents the development of a lightweight prefabricated floating apartment as a response to the specific local natural conditions and increasing demand for spending time on water.

METHODS

RESEARCH BY DESIGN

To address the aforementioned aim, the empirical design-driven approach, as described by BREEN [2002], was adapted. The empirical research approach aims at verifying design hypotheses in simulation and experimental conditions.

The presented research covers design and evaluation of a prototype floating apartment located at the Lake Roś in the Masurian Lake District (Fig. 1a) commissioned by a private investor. The design works were conducted in 2018 in the group of two architects supported by a structural engineer. This paper highlights both the design process and implemented techniques as well as the final result.

DESIGN CONSTRAINTS

A. Environmental conditions

The site sits at the end of the 1-kilometer-wide southern valley of the tunnel-valley Lake Roś. The local depths vary from 0.5 m at the wharf, where the house was built, up to 3.5 m at the end of the 40-meters-long floating jetty, where it was finally located (Fig. 1b). A large wind exposure of the site combined with the decreasing depths results in difficult wave conditions during the winds from directions from NW to NE.

B. Functional conditions

The site belongs to a larger hotel establishment with private waterfront and resident marina. Its adjacency to the on-land main hotel building allowed to narrow down the functional requirements of the designed apartment. Most importantly, close proximity to the dining facilities allowed us to reduce the apartment's kitchen program. Considering the above, the program included:
1) living space,
2) bedrooms for 4 people with the possibility to accommodate another 2,
3) bathroom,
4) circulation,
5) technical space.

C. Aesthetical conditions

Basic aesthetical decisions were driven by the idea to keep the architecture simple in order to focus the user's experience on water and by the intention to fit the designed form into the context. Therefore, it was decided that the building should feature a gable roof, simple materials and possibly neutral colours.

D. Technical conditions

There were three basic technical constraints in the design process: draft, stability and construction time of the floating apartment.

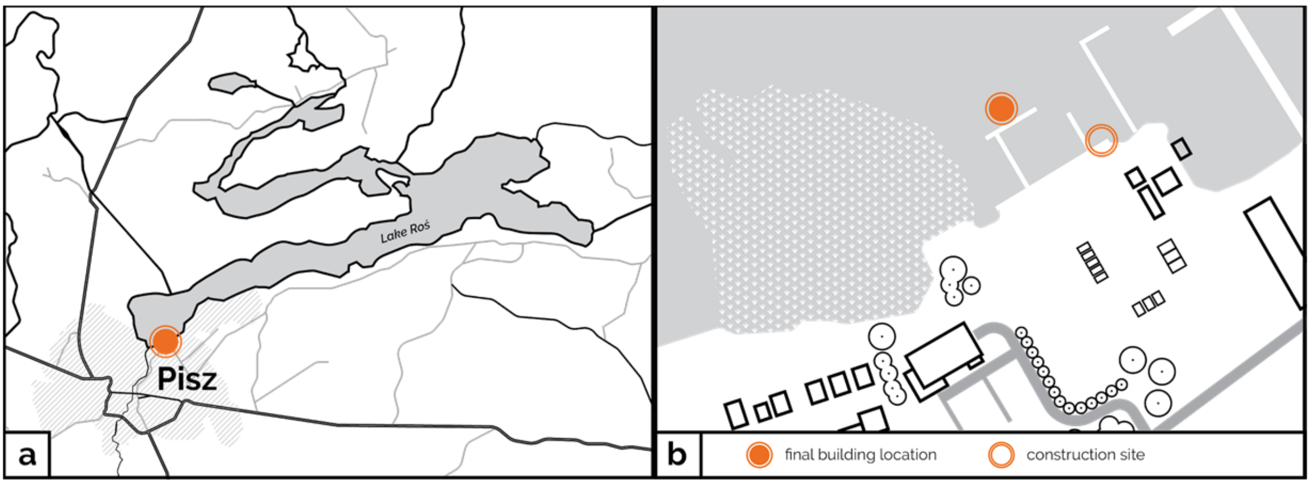

Fig. 1. Project location, a) geographical context, b) building's final location; source: own elaboration

The building was to be erected close to the lakeshore, where the water was approximately 0.5-m deep. Such location provided the contractors a comfortable access to the building structure. At the same time, the shallow site forced us to reduce the building draft in order to avoid grounding and to allow for its safe transportation to the final location after the construction. Therefore, the initial draft limit was assumed 0.3 m.

The stability criteria were set according to "Rules for the classification and construction of inland waterways vessels. Part IV, Stability and freeboard", defined for floating platforms: in case all people on board crowding towards one side and a steady wind pressure acting on the other side, the angle of heel shall not exceed 6°, the bilge shall not emerge from water and residual freeboard shall not be less than 0.05 m [PRS 2019].

Furthermore, the construction during the tourist season required searching for means of decreasing the construction time. This requirement was addressed by introducing prefabricated structural elements, which can be implemented for floating urbanization [MOHAMAD *et al.* 2012]. According to ALBUS [2018] prefabrication of structural elements reduces construction time even by 95%. This approach forced the use of standardized modular floating pontoons as a building foundation which constrained the building footprint dimensions to 7.86 m length and 5.99 m width.

E. Legal conditions

According to Polish legislation, stationary floating structures are water vessels, not buildings [KURYŁEK 2017]. In the presented prototype's case it was decided with the client to register it as a pleasure yacht. Mooring vessels of this kind and size in the hotel marina was regulated by the water law permit issued by local administration. As the floating structure didn't have to comply with the building code, some level of flexibility in experimenting with combining civil and naval architectural design approaches was allowed. Nonetheless, the superstructure was designed according to civil engineering standards, which was a major difficulty in achieving a lightweight building [OLTHUIS, KEUNING 2011].

DESIGN SIMULATION

A. Design integration

The technical constraints of low draft and sufficient stability required looking for methods that allow to control the structural properties in a real-time during the design process. Therefore, the design phase involved creating a multidisciplinary digital simulation of the designed apartment. The design was developed and coordinated with the use of Building Information Modelling (BIM) approach. The architectural design was modelled and coordinated with other disciplines in the Autodesk Revit software.

B. Buoyancy and stability simulation

The stability simulation was performed on the integrated BIM model. For accurate results, the model required the Level of Development (LOD) of at least 300 [Designing buildings 2019]. The dynamic relation between the model and the simulation was established through custom solution developed in the Dynamo for Revit environment. The process workflow is shown in Figure 2. The algorithm examined the model geometry along with its associated parameters. For the simulation purposes, a local coordinate system (LCS) was defined. Its origin $P_0 = (0, 0, 0)$ was set on the ground floor level, in the geometric center of the building footprint. The model elements can be divided into two groups:

1) composites, such as walls, floors and roofs, which consist of multiple material layers,
2) solid objects, such as windows, doors, furniture and fixtures.

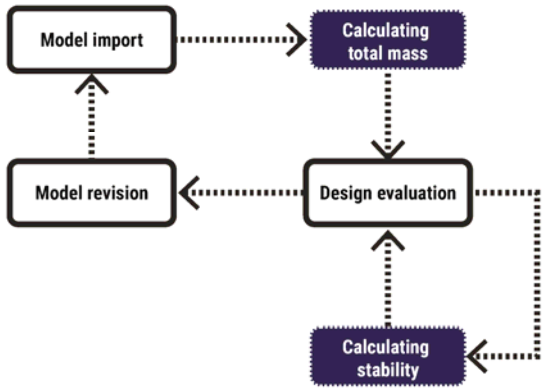

Fig. 2. Stability simulation process workflow; source: own elaboration

For composites, the algorithm calculated the mass m and the center of mass $c = (c_x, c_y, c_z)$ separately for each material layer. In the analysed case the centers of mass align with the elements' geometric centers (centroids). The material mass was computed based on the layer volume and predefined material density. The center of mass was computed based on the 3-dimensional layer geometry. For solid objects, the algorithm got the predefined value of the mass parameter and calculated their centroids as in the case of composites. In order to simplify calculations, solid objects were assumed to be made of single materials. The obtained values were then used for calculating the heeling moment for each element, and then for computing the resultant mass, center of mass and the heeling moment for the whole building. The calculation could be automatically updated each time the model was revised.

In the next step, the data from the digital model of the house were used to calculate the draft, freeboard height, minimum freeboard heeled and maximum heel angle. This part, due to editing reasons, was done in MS Excel. Such workflow allowed us to control buoyancy and stability of the structure at every point of the design process.

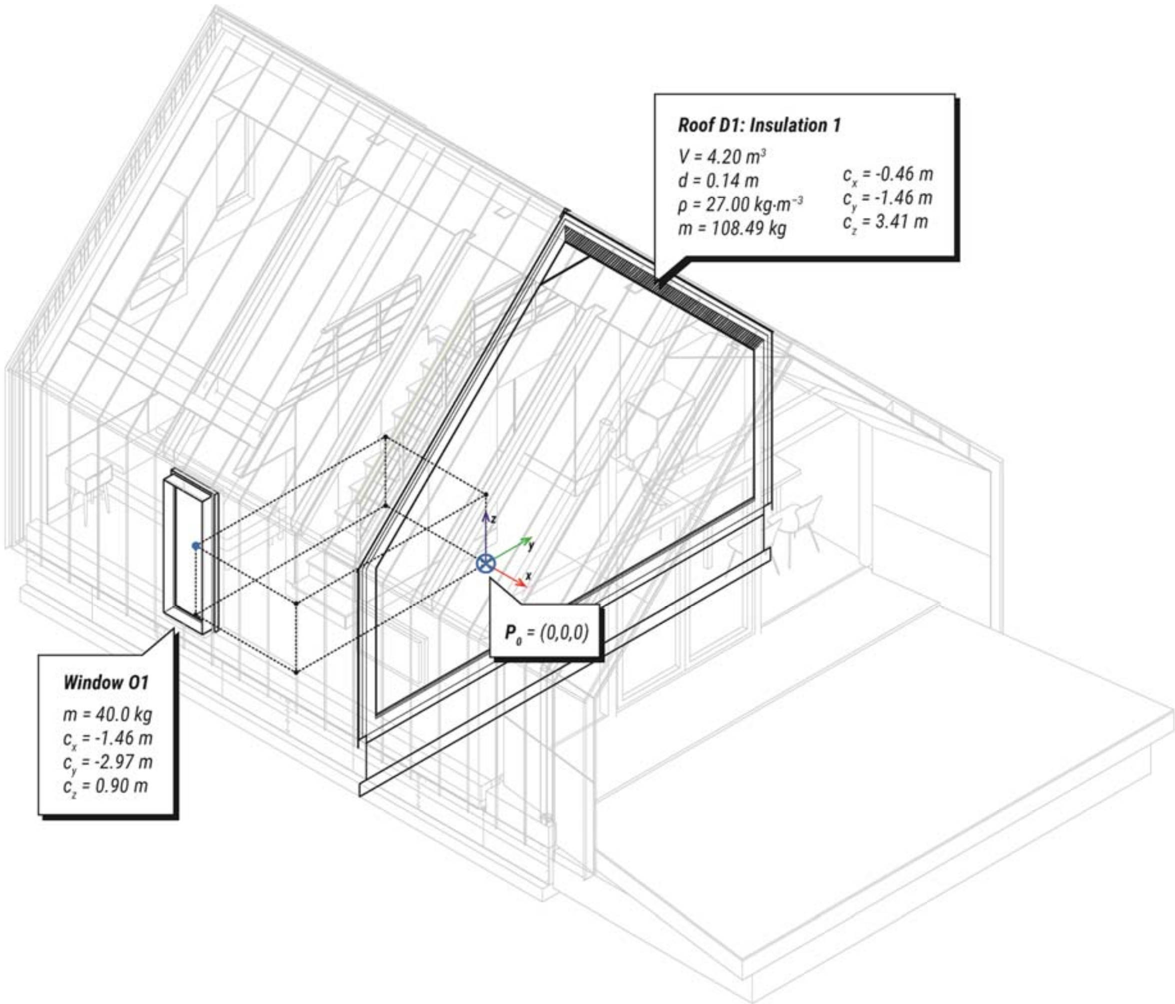

Fig. 3. Axonometric scheme of the geometry analysis; *V* = volume, *d* = layer thickness, *ρ* = material density, *m* = mass, *c* = center of mass, *Po* = model origin; source: own elaboration

RESULTS

GENERAL DESIGN DECISIONS

The prototype can be considered a typical floating building according to the criteria defined by PAK [2011]. In order to minimize the draft and the risk of tilting, the building features the following characteristics:
1) symmetrical plan: balanced distribution of building elements in order to minimize the building's resultant heeling moment,
2) sloped roof: reduction of the upper floor area and volume in order to lower the building's center of mass and avoiding the mass of the snow in winter at the same time,
3) lightweight materials: decreasing the total building weight.

LAYOUT

The layout was created according to the common rule: the waterside facade is open and transparent to maximize the views and enhance the user's contact with nature while the landside facade is closed to ensure privacy and safety [NILLESEN, SINGELENBERG 2011]. As a result, the living room was located by the glazed wall and other rooms (bedroom and bathroom) under the mezzanine on the opposite side of the building (Fig. 4).

AESTHETICS

In order to take advantage of the water location, a roof without eaves and gutters was designed. The goal was to let the rainwater come down the walls on which the steel roof sheets continues. The roof and the side walls have been covered with Rheizink titan-zinc sheets (angle seam) in neutral grey colour. It all resulted in a form of a "modern barn" with an all-glazed gable wall on the waterside (Photo 1).

LIGHTWEIGHT MATERIALS

The building was founded on a styrofoam floating system platform. The platform consists of a steel-frame structure and a light styrofoam infill (water absorptivity below 3%), which makes it significantly lighter in relation to other floating solutions.

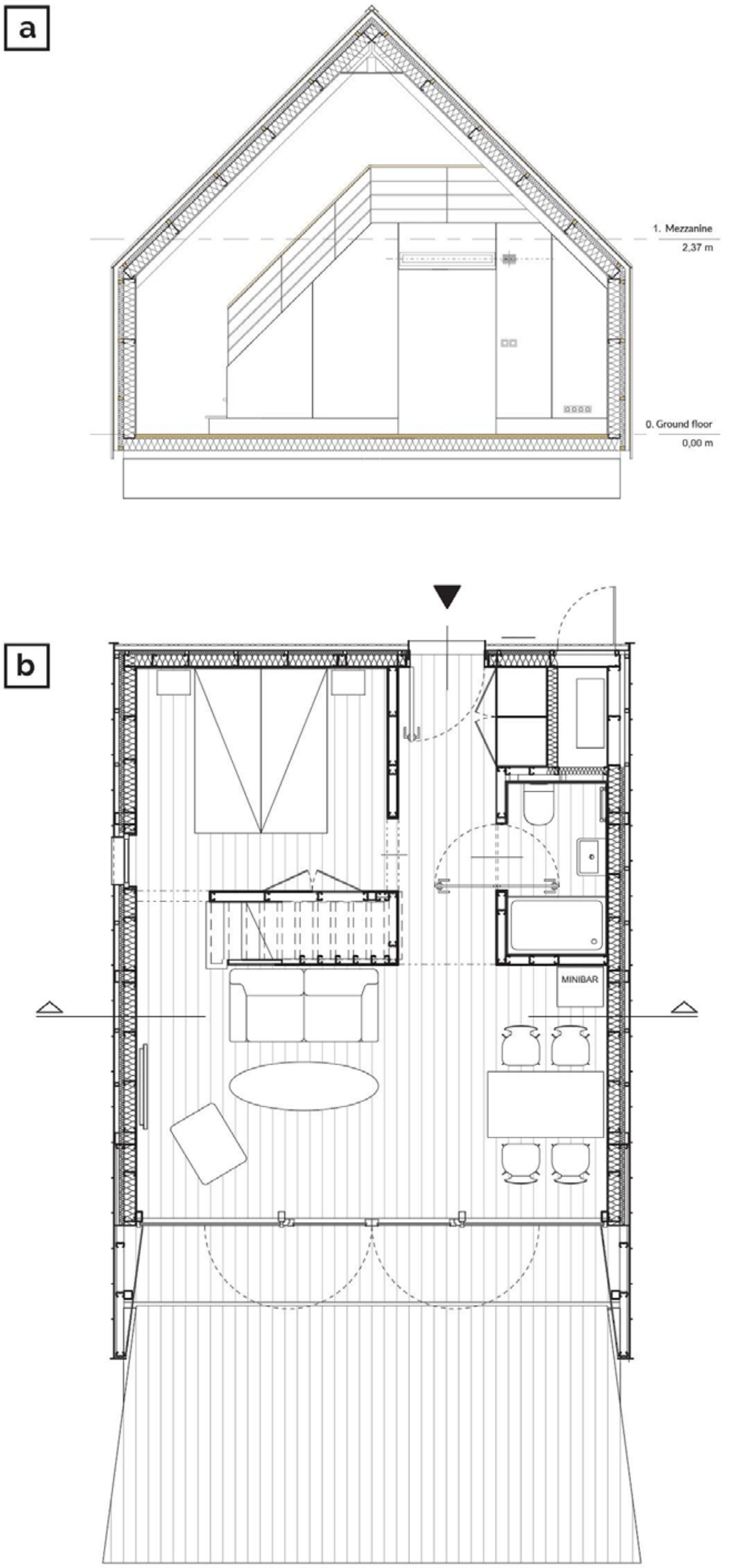

Fig. 4. Building design: a) cross-section, b) ground floor layout; source: own elaboration

Photo 1. Completed prototype floating apartment at Lake Roś in Pisz (phot. *K. Ostrowska-Wawryniuk*)

Fig. 5. Scottsdale Construction System structure raised on the steel and styrofoam platform before insulating; source: own elaboration

The building structure was built with a Scottsdale Construction System (SCS), which is lighter than other technologies, such as timber or steel frame typically used in floating structures (Fig. 5). This weight reduction is obtained with thin-walled cold-formed galvanized steel C-sections. The C-section assures proper structural stiffness despite of only 1 mm profile thickness. The CNC manufacturing assures high quality and precision [Scottsdale Construction Systems 2019].

PREFABRICATION

In the presented apartment design prefabrication was limited to floating foundation platform and steel frame structure.

The steel-frame styrofoam floating platforms are manufactured in panels that may be transported by roads. The construction of the presented building required connecting two such panels alongside in order to form a building platform of the required size. The platforms were floated separately and joined on water.

The SCS structure was delivered to the construction site in prefabricated steel-frame panels. The panels were manufactured with high precision according to the architectural requirements. As a result, the on-site structure assembly lasted only three days.

BUOYANCY, TRIM AND STABILITY

The BIM-based evaluation system turned out to be an effective approach. The initial trim analysis revealed that the first design iteration required balancing due to the excessive weight of the all-glass gable wall and combining all service equipment in one building corner. Precise calculations of mass of the building allowed for adjusting the floating system before the erection of the superstructure has started. The results of the final draft simulations were confirmed on the prototype.

DISCUSSION

BIM FOR STABILITY CALCULATION

The BIM-based approach allowed for integrating all design stages in a single digital model. Enhancing the BIM possibilities with custom scripting enabled us to analyze the model in a way that is atypical in architectural design. For each model element, it was possible to obtain its accurate position in the LCS and its mass. Since these two parameters have a direct impact on the overall building's stability and total mass, a thorough control of these parameters' values was crucial for the whole detailed design phase.

Implementation of a custom Dynamo for Revit solution allowed us to establish a dynamic relationship between the architectural model and the stability analysis output. The analysis could be automatically updated after each alteration to the model. As a result, thanks to the significant reduction of time necessary for the manual calculation, multiple design alternatives could have been explored.

It is important to point out, that the aforementioned BIM solution was a working prototype and as such, had its limitations. First of all, geometry processing for certain groups of objects was computationally ineffective due to Autodesk Revit's internal calculation methods. Some of Revit native elements, such as curtain wall mullions, required additional processing in order to allow for proper volume and centroid calculation. This additional step increased the overall algorithm complexity. Moreover, the simulation revealed Revit's weaknesses in terms of handling complex solids, such as pieces of furniture compound of multi curvature surfaces. Some of these elements required geometry simplification in order to return proper values.

Lastly, the stability analysis was performed on a relatively small model, consisting of 330 elements. The complete calculation for the whole model lasted almost 5 min. This performance is inefficient compared to other 3d modelling software supporting computational geometry processing, such as commonly used Rhinoceros with the Grasshopper extension. In order to overcome this limitation, the solution was extended with the element selection feature. The additional function allowed for performing the calculation only for preselected model sections. As a result, simulation time could be significantly decreased as the calculation was performed only for model sections that were altered in the design process.

The Building Information Modelling proved to be a valid option in terms of integrated project delivery. However, a universal solution requires additional work. Without further algorithm optimization the solution might turn out useless for more complex designs, containing many more elements and more complex geometry.

PREFABRICATION

The construction phase benefited from implementing prefabrication techniques. Prefabrication techniques turned out to be successful. The SCS system proved to be easy and fast to assemble. It would be reasonable to introduce more prefabricated elements, starting from the thermal insulation panels for walls and roof. This should go along with reducing the number of girders that were difficult to insulate.

SCOTTSDALE CONSTRUCTION SYSTEM (SCS)

SCS system proved to be an appropriate solution for floating construction, as it is lightweight and easy to prefabricate. Despite these advantages, the system revealed also a serious drawback, that is, a problem of insulating a complicated SCS girder frames. In order to minimize the wall thickness and save the interior space, the girders were designed as small as it was possible to manufacture. However, that made them difficult to fill in with insulation. This issue was addressed by introducing a polyurethane spray insulation which can fit into atypical girders' geometry. At the same time, spray insulation generated a risk of water pollution, which made it complicated to apply on-site.

Furthermore, the prototype revealed that it is impossible to combine the pure SCS structure with the fully glazed facade. Due to the high structural stiffness required by the large glass panels, the SCS structure had to be reinforced with hot-rolled steel profiles, which reduced the mass savings achieved with the SCS.

LOW DRAFT, LOW MASS AND STABILITY

It was found that a lightweight building with low draft may have sufficient stability, as it is more the result of the underwater shape than the height of the center of mass. This finding is counterintuitive and therefore requires further research. At the same time, low mass results in a low inertia, which is insufficient for stronger waving. Even though the house does not heel much, it is susceptible to larger waves that may generate unpleasant shocks when reaching the building. This can make the users feel insecure. This phenomenon should be taken into consideration in all locations exposed to wind and waves. In Pisz, this problem was solved by special semi-rigid jetty attachment system of three joints between the float of the house and the concrete mooring floating jetty. Rapid movements of the floating apartment are suppressed in two ways. Firstly, by the rubber dumping pads in the joints. Secondly, by the large inertia of the pair of floating structures, the house and the jetty [Mazurkiewicz 2004], hold together at a fixed distance of 7 cm thanks to the steel bolts in the joints.

CONCLUSIONS

This paper presented experiences with designing and managing construction of a floating apartment building for shallow inland waters. It introduced all stages of the process: from planning and site analysis to iterative design and to its execution.

The idea of experimenting with a lightweight, low-draft building moored to a heavy concrete jetty turned out to be successful. Our experience with realizing the prototype shows that a carefully planned design phase plays an essential part in the overall process. The integrated digital model of the building allowed us to simulate the building's performance and significantly enhanced the decision making in the process.

For the future realizations increasing the level of prefabrication is recommended in order to further reduce the site work time and difficulties related to construction on a floating platform. In the presented case the level of prefabrication resulted, above all, from the small scale of the investment. Furthermore, the scope of prefabrication was also constrained by technological limitations of facade finishing elements such as aforementioned all-glass gable wall or titan-zinc roofing plates which were applied on the roof and sidewalls.

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