BIM-Aided Prefabrication for Minimum Waste DIY Timber Houses

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The continuous housing shortage demands efficient ways of design and construction. In the context of rising construction standards and shrinking manpower, one of the possible answers to the problem is prefabrication oriented towards do-it-yourself (DIY) construction methods, which could contribute to the low and middle income housing supply in the market. The article covers the process of developing an experimental tool for aiding single-family housing design with the use of small-element solid timber prefabrication, suitable for DIY assembly. The presented tool uses the potential of BIM technology adapting a traditionally-designed house to the needs of prefabrication and optimizing it in terms of waste generated in the assembly process. The presented experiment was realized in the Autodesk Revit environment and incorporates custom generative scripts developed in Dynamo-for-Revit. The prototype analyzed an input model and converted it into a prefabricated alternative based on the user- and technology-specified boundary conditions. The prototype was tested on the example design of a two-story single-family house. The results compare the automated optimized model conversion with manual adaptation approach. The implemented algorithm allowed for reducing the construction waste by more than 50%.

Keywords: do-it-yourself construction, do-it-yourself house, generative BIM, BIM-aided prefabrication, small-panel timber prefabrication, self-help housing

INTRODUCTION

Prefabrication is nowadays a standard in housing construction in many countries worldwide. It is considered faster, safer, cleaner and, due to the benefits of mass production, also cheaper. Contemporary prefabrication features a wide range of technologies, varying in terms of prefabricated element size, function and material. Furthermore, the mass customization paradigm significantly increased the variety of possible design outcomes. That, along with the development of CAAD and - more recently - BIM opened a whole new world of opportunity before architects.

From the historical perspective prefabrication was usually associated with modularity. A prefabricated building was constructed with limited number of components significantly decreasing the variety of possible outcomes. This kind of highly repetitive typified architecture is characteristic for mid-20th cen-
tury low quality concrete large panel systems, popular especially in Central and Eastern Europe. According to Tatjana Schneider and Jeremy Till in most cases this kind of prefabrication proved to be ineffective in terms of building flexibility. Simultaneously, flexibility is commonly referred to as a determinant of a well-designed housing. A house or apartment should be adaptable to users’ needs changing over time. Most of the known prefabricated housing fail to meet this requirement (Schneider and Till, 2007).

The analysis of existing examples of prefabricated housing raises important questions about possibilities of increasing its flexibility. The overview of past as well as currently available prefabrication technologies reveals a general pattern: the degree of flexibility increases in proportion to manual workability of used material and in inverse proportion to the size of prefabricated elements. At the same time, it is noticeable that contemporary prefabrication trends towards large ready-made modular volumetric units. Volumetric prefabrication offers significant reduction of construction time. The prefabricated modules are practically ready to be used right after the assembly on site. On the other hand, this kind of prefabrication is highly ineffective in terms of transportation cost as well as flexibility.

As pointed out by Nikos Salingaros and Débora Tejada an alternative to modular design is creating a structure through subdivision of the architectural form. This approach allows the structural components to take any dimensions and shape, freeing the architecture and its future users from the limitations of a rigid modular design (Salingaros and Tejada, 2001).

Salingaros’ approach converges with the philosophy of Walter Segal - one of the distinguished architects of the 20th century. Segal is known for his self-build method in which adaptability can be achieved with the prefabrication with simple materials such as timber. Segal’s method assumes using standardized yet flexible elements rather than inventing a new standardized system. Additionally, his approach enables users to build homes on their own (McKean, 1989). It extends the meaning of flexibility by introducing the do-it-yourself (DIY) method which not only allows unqualified users to construct their own houses but also to alter them according to their needs changing over time. Furthermore, the term ‘flexibility’ can be applied to the material itself, as timber can be processed both by machine and manually on-site in order to achieve the desired outcome.

These observations encouraged me to explore possibilities of applying a small-panel solid timber prefabrication to achieving flexible and easy to build houses. Along with the flexibility, timber is also a sustainable material, which is a significant factor in terms of developing universal solutions. At the same time, small panels are easier and cheaper to transport and offer a good structural performance.

RESEARCH BACKGROUND
Problem Statement
This paper covers a prototype solution for adapting a single-family house design to the purpose of a DIY-oriented timber prefabrication. The objective was to make a small-element solid timber prefabrication (Fig. 1) a relevant alternative to traditional construction technologies as well as other prefabrication techniques. At the same time, the presented solution aims at preserving the architectural diversity by applying the mass customization paradigm. To address this issue, I proposed an algorithmic BIM-based tool which enables automatic generation of geometry of prefabricated timber panels based on the input model. The goal was to maximize benefits of mass production by generating as many repeatable elements as possible.

The main advantage of using a solid timber structure is that the non-repeatable elements can be achieved either with off-site CNC fabrication techniques or by manual on-site adjustments. The minor manual adjustments can be performed by unqualified user, which significantly increases the building’s flexibility potential. Additionally, due to the solid timber structure there are no limits in terms of interior arrangement, in terms of casework for example, which
further increases the flexibility. Due to simple carpentry joints between panels the partition walls can be demounted and placed elsewhere according to the user needs. At the same time, timber is a carbon-negative material and, due to moisture diffusion, it provides a good living microclimate.

**Related Work**

In the recent years fabrication techniques in the building industry have witnessed a major advancement. A modern approach to prefabrication answers the needs for architectural diversity. Technology and methods of contemporary prefabrication were addressed in a book *Robotic industrialization: automation and robotic technologies for customized component, module, and building prefabrication* by Thomas Bock and Thomas Linner (2015). In this publication they present industrial solutions for both typical and custom developments, designed with most commonly used materials, such as brick, concrete, wood and steel. They also address the design specificity, flexibility and sustainability of prefabrication with each material.

Simultaneously, the problem of DIY approach to housing is not widely addressed in recent research in the field of housing. There are few publications undertaking this theme. Among these it is worth to mention the *Self-Help Housing* by Peter Ward (2019) who analyzes this issue from historical and social perspective. He highlights that the DIY and self-help construction approach was a result of the private and public sectors’ inability to meet the housing demand.

In the context of CAAD and computational design the problem of DIY houses was undertaken by Chung Man Cho and Wei Mu (2013) who proposed a glued bamboo (glue-bam) prefabricated construction system integrating computational design application with material to achieve DIY housing.

The issue of BIM-aided prefabrication was undertaken, among others, by Mohammed Mekawy and Frank Petzold affiliated with Technical University of Munich. Mekawy’s research focused on concrete prefabrication in large scales: volumetric modules (Mekawy and Petzold, 2017) and large panels (Mekawy and Petzold, 2018). Whereas the first paper presents an exhaustive method of generating all possible solutions, the latter work presents an au-
tomated rule-based system for early design phase evaluation. Similar approach can be found in the “SeeBIM” prototype (Belsky, Sacks and Brilakis, 2016) which identifies topological relationships between concrete design elements.

**METHODS**

The prototype was developed for the Autodesk Revit environment extended with Dynamo and custom scripts. It operates on a standard BIM model from which it extracts the information about the building structure. The algorithm collects the positions and dimensions of walls, slabs and roofs, as well as openings such as windows and doors, and organizes them hierarchically according to level, category, host (for openings) and type (Fig. 2).

**Prefabrication Constraints**

In the first phase, the algorithm computes the maximum sizes of prefabricated elements. For walls, the maximum panel width is calculated based on the building level height, assumed wall thickness, user-defined maximum weight and average structural wood density. In terms of slabs and roofs, the level height is replaced by the slabs’ span. In the assembly process the panels are joined with grooves milled on each vertical edge as shown in Fig. 3. The effective panel coverage is therefore reduced by the width of the grooves, that is, approximately 15 mm [1]. Additionally, due to fabrication constraints the panel width should be a multiple of 4 and should not be smaller than 36. In further phases the algorithm uses the calculated values as a boundary conditions for wall and slab panelization. In this paper the panels of maximum allowed width will be further referred to as standard panels.

The small-panel timber prefabrication requires introducing additional constraints. In order to assure a proper structural stiffness each wall needs a foundation and cap beam of 100x100 mm profile, which decreases the height of a standard panel by 200 mm. For the same reason, each windowsill needs to be capped by a similar beam. Furthermore, like in traditional construction, both windows and doors require a head beam which spans over panels directly neighboring the opening (Ostrowska-Wawryniuk and Stepniak, 2018). The typical subdivision of a wall is shown in Fig. 4.
**Splitting and Panelization**

In the second phase the algorithm examines the model in order to obtain its geometric structure. The walls are simplified to their location lines (centerlines). External wall location lines are then combined into polygons and partitions into open polylines. The openings are then projected onto location lines indicating the span of each opening in its host wall. The obtained data is organized according to the hierarchy of data in the base model.

Afterwards the splitting routine generates a preliminary division scheme containing a collection of split points on the wall polygons and polylines. The location of split points fits the aforementioned prefabrication constraints. Due to prefabrication constraints the division might result in a number of non-standard panels. In the next phase the division scheme can be further optimized in order to minimize fabrication cost and construction waste.

The division scheme is then appended with the pattern of wall foundations and caps, as well as opening caps and heads.

**Optimization**

In buildings that are not designed with modularity in mind it is almost impossible to achieve a perfect repeatable panelization. In most cases the resulting structure features several non-repeatable elements which usually appear in walls’ endings. These custom panels can be fabricated off-site. However, the advantage of applying timber panel prefabrication has also the potential of achieving non-standard elements by manual on-site adjustment of the standard ones.

In case of small number of non-standard panels, the manual manipulation is cheaper than off-site CNC fabrication. Therefore, apart from automating the panelization process the goal was to minimize the waste generated in the process.

In the proposed solution the panelization is generated in such a way that the maximum possible number of non-standard elements can be combined into larger standard panels. In other words, in the proposed solution the leftovers, such as cut-offs appearing at wall endings, can be reused elsewhere in the structure. In order to enhance the optimization, I introduced an additional module parameter, which allows for adjustment of the standard segment width to further minimize the material waste.

The optimization is conducted based on the algorithm which balances the three criteria:

1. The maximum panel width: the algorithm prefers the highest width obtainable with the predefined weight constraint.
2. The minimum waste: the algorithm prefers the panelization where the most leftovers panels can be reused in other parts of the structure.
3. The minimum type count: the algorithm prefers the solutions with the most repeatable panelization.

**Geometry Processing and Documentation**

The final panelized geometry was achieved by creating parts for each structural component. The parts were then split on the basis of the division scheme. Afterwards each panel is assigned with a unique id number necessary for on-site assembly.

Finally, for each building wall the program generates a shop drawing and detailed schedule for fabrication and assembly.

**RESULTS**

The prototype was tested on the example two-story single-family house with the area of 80 m², story height without finishing of 271 cm and external walls perimeter of 32,24 m (Fig. 5). With timber panel structure the wall thickness could be reduced to 10 cm allowing for saving approximately 3,2 m² of space in comparison to traditional technologies. Since each timber wall required a 10x10 cm foundation and cap beam in order to assure the proper stiffness, therefore, the effective height of a prefabricated wall panel was 251 cm. The analyzed building requires 25,27 m³ of solid wood for all structural components.
For panel size calculation the average wood density was set to 450 kg. In order to enable the assembly to be pursued by two people the maximum panel weight was set to 50 kg. Based on the above constraints the maximum calculated panel width was 44.26 cm. This value was then rounded downwards to 44 cm in order to meet the fabrication requirement of width being multiple of 4. The resultant standard panel measured 44 x 251 x 10 cm.

In manual division process the panelization is determined for each wall separately, starting from an arbitrarily selected end. This kind of approach results in the highest waste rate. For the standard panel division the non-optimal total panel count was 282 (Fig. 6a). The outcome included 146 full standard panels, 14 panels requiring manual or CNC adjustment due to window openings, and 26 panels of non-standard width on wall endings. Only 4 of these irregular panels could be combined into standard-sized elements. Additionally, there were 6 shorter panels under wall openings, which could also be combined into standard panels and 20 shortened panels neighboring door openings. Similarly, 78 shorter panels appear also in the attic level. These panels, however, can be produced in their final size during fabrication. For the standard non-optimized panelization the construction would produce 26 cut-off elements (1.05 m³) of waste which stands for 4.2% of the total timber required for the construction of the analyzed house.

The optimized distribution of standard panel division (Fig. 6b) featured a better adaptation of the cut-off elements. It allowed for reduction of the waste generated by cut-off ends by 0.55 m³ (52%) although the panel count remained the same. Afterwards the algorithm tested decreasing the standard panel width by 4 cm to 40 cm and then to 36 cm. This process improved the solution by 70% and 64% respectively in comparison to the non-optimized outcome (Fig. 6c and 6d).

Surprisingly, the panelization with the standard panel width of 40 cm turned out to be the best in terms of waste minimization. As expected, the narrowest panels provided the closest fit in the base structure, but at the same time, they generated the biggest number of short cut-offs that could not be adapted elsewhere. In the panelization with 40-centimeters panels over 50% of cut-offs were wider than 20 cm and therefore, could be adapted.
DISCUSSION
The aforementioned results show that implementing an automated routine to the panelization phase could contribute to decreasing the amount of waste in the process of the small-element solid timber house assembly. In practice, the subdivision process is often performed manually. As a result, it is pursued when the design phase is concluded. Consequently, due to time limitations, the final solutions are rarely optimal, since adjusting them would require repeating the whole process. Considering that the proposed solution is scalable, I believe that the material efficiency could be even more distinct in larger developments.

By implementing timber structure, I hope to not only increase the building’s flexibility, but also enhance its sustainability. In the context of global changes such as global warming and shrinking resources, turning towards renewable and climate-friendly materials is a crucial step in housing development.

The presented BIM-based tool allowed for a real-time simulation of a prefabricated construction. The simulation could be adjusted according to the changes in the building design, which has the potential of improving the decision-making process and design sustainability in early design stages. The original BIM model could be utilized to compare and contrast different options based on multiple criteria.
Finally, the DIY approach responds to the arising demand for bringing the designers closer to their clients. Simultaneously, by limiting the number of qualified workers in the construction process, the solution could significantly decrease the total cost of investment, which addresses the demand for affordable housing. Similar idea was introduced by Cho and Mu (op. cit.). Their idea, however, utilizes glued bamboo (glue-bam) instead of solid timber. This approach converges with Peter Ward’s observation that self-help is a significant driver of low-income housing development, especially in the areas of rapid urbanization.

Although the scope of this paper is limited to small-panel timber prefabrication, the presented prototype is a part of wider research in the field of utilizing BIM environments for design with the use of prefabrication. The prototype will be further developed in order to become a computational aid for participatory design of single-family houses and, furthermore, also multi-family developments realized by housing cooperatives. The aim is to create a multidisciplinary interface bringing together architects’ creative freedom, structural and fabrication requirements and the ultimate user’s needs.

REFERENCES


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