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APPLYING GENERATIVE DESIGN IN INDUSTRIALIZED HOUSE BUILDING? – PREREQUISITES

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Abstract

Practitioners in the traditional construction have successfully been using generative design for optimization of building projects, however there is limited knowledge on these applications in industrialized house building. This study therefore identifies the current level of digitalization, BIM interoperability and platform flexibility as prerequisites for generative design applications in a case study. The level of digitalization and BIM interoperability are currently not at a high enough level to support the full use of generative design. However, platform flexibility for single-family housing built in panelized elements and multi-family housing built in volumetric elements can enable use of generative design applications.

Introduction

While the traditional construction industry is one of the biggest engineer-to-order industries (Gosling and Naim, 2009), industrialized house building (IHB) is specialized in off-site manufacturing of housing using modular product design as a base for mass-customization, which enables companies to use standardization in products and processes and at the same time offer predefined customization possibilities (Robertson and Ulrich, 1998). IHB companies achieve this by implementing platforms where product solutions are designed to fit a building system that sets the design limits according to the legal requirements, off-site manufacturing systems and the supply chain (Meyer and Lehnerd, 1997). However, platforms implemented by IHB companies have varying levels of pre-engineering work done before customer orders (Johnsson, 2013) that are produced in off-site manufacturing systems using varying levels of prefabrication (Jonsson and Rudberg, 2015), hence having different levels of flexibility.

Generative design software is currently used by architects and engineers to identify optimal design solutions more efficiently (Aksamija, 2018). The general way to implement generative design in BIM is to set-up rule-based parameters that govern the shape and placement of objects and telling the software what these parameters should apply to (Harding and Shepherd, 2017). The usage areas of generative design are by example light studies, space planning and cost estimations.

The design limitations set by building systems steer the development of optimal pre-engineered solutions. Similarly, the design process for the client orders combines pre-engineered solutions with varying customer requirements and local building regulations which often leads to specific design solutions consisting of compromises, where the best solution is often the “least bad” solution (Marsh, 2008). Generative design could be a potential solution to this since the multi-parameter models can aid in the design process of both pre-engineered and specific design solutions (Bianconi et al., 2019). Generative design that follows building system can aid in achieving efficiency in off-site manufacturing processes, while still enabling customization within the solution space (McKnight, 2017). In mass customization, aspects like complex design shapes and unique solutions will be set aside in favor of optimization of raw material use and production efficiency (Monizza et al., 2017). Therefore, off-site manufacturing systems are potentially a limitation to generative design use in mass customization context such as IHB, in case they limit the building system solution space to high extent (Monizza et al., 2018). Digitalization and BIM interoperability can help introduce a higher grade of detail earlier in the design process (Bianconi et al., 2019), where parametric functions like generative design could then be applied (Wikberg et al., 2014).

Based on the previously mentioned studies, generative design shows potential in aiding the design process when developing optimal solutions both as part of pre-engineering as well as for the client orders. However, in order for IHB companies to take full advantage of the use of such methods, two main prerequisites must be in place to enable it (Chang et al., 2019). The main prerequisites are the level of digitalization and BIM interoperability, as well as platform flexibility to accommodate necessary changes in product design. Not being able to fulfil these could result in problematic or meaningless implementation of generative design (Hernández et al., 2021). IHB companies therefore need to have the prerequisites aligned with the appropriate uses of generative design to avoid these pitfalls. The aim of this research is to identify the current level of digitalization, BIM interoperability and platform flexibility present in IHB as prerequisites for generative design applications. The case study was conducted in one of Sweden’s largest IHB companies that uses three different platforms. The prerequisites for generative design applications were studied by collecting and analyzing empirical data regarding their design processes for both pre-engineered and specific design solutions, used software, building systems, and off-site manufacturing systems.

Theoretical background

Industrialized house building

Traditional construction companies mostly operate on an engineer-to-order production (Gosling and Naim, 2009). However, industrialized house building (IHB) companies design their products using platforms and lean production strategies (Lessing, 2006). This also results in a shift of focus, from project to process- and product focus (Goulding et al., 2015) where significant amount of pre-engineering work takes place. Technical platform, hereof referred to as building system, is a generic description of all individual house parts and their interfaces. A building system is developed to address legal requirements as well as the capabilities and limitations of off-site manufacturing systems and supply chain. Advanced information systems are needed to support the design process for client orders that follows building systems and thereby prepares for the supply of materials, prefabrication in factories and on-site assembly (Gann, 1996).

When it comes to the design and architecture of the buildings and modules, there is a divide between architects, where some architects resist this type of prefabrication, while others accept it (Lessing and Brege, 2018). Jansson et al. (2018) found that architects working with modular products felt a need to understand the building system to be fully capable of creating a design that can be efficiently produced, emphasizing a need for effective communication and organizational relationships. Effective communication then also enables the transfer of experience from a completed project back to the development processes (Goulding et al., 2015). There are also concerns about change in the digital work process in IHB, where the new digital work process has to be adapted and tailored to fit the existing organization (Lessing and Brege, 2018). To allow the architects and designers the flexibility they want, while still providing a product that is possible to produce at the rapid pace that the IHB companies do, the demand for advanced design tools that can handle this type of design is high (Olofsson et al., 2010).

Generative design

Generative design is a method used mostly to generate various proposed models based on a parametric model along with various algorithms and constraints (Harding and Shepherd, 2017). This is the most powerful use of generative design, as it allows the software to find solutions to problems which can then be used by human designers for decision making, saving the designers the time it would have taken to find and draw all of the designs on their own (Eriksson et al., 2019). There are also numerous rules and regulations a building must comply with, and manually checking all of these on a per-design basis can both be time-consuming and leave room for mistakes (Ismail et al., 2017). Several uses for generative design within architecture and traditional construction have proven successful. Generative design can by example aid: planning a neighborhood (Nagy et al., 2018), energy efficiency studies (Caldas, 2008), floor plan studies (Hu et al., 2020, Zhang et al., 2021), furnishing optimization (Sydora and Stroulia, 2020), sustainability checking (McGlashan et al., 2021), optimization of drywall layouts for offsite production (Cuellar Lobo et al., 2021), optimization of the construction site planning (Mohammed Fathy et al., 2022), optimization of costs based on structural design (Hernández et al., 2021) and optimization of production times of panelized elements (Liu et al., 2021).

Exploring different options at the beginning of the design process can be beneficial for optimizing the end design, however the method does have some caveats that designers need to take into consideration (Amadori et al., 2012). Multi-criteria performance brings a lot of complexity to projects and need a lot of careful evaluation in order for the generative design process to provide substantial results (Chang et al., 2019). When optimizing for multi-criteria problems it is therefore required that the designers have an in-depth knowledge of the problem at hand, as well as the primary purpose of the generated solutions (Hernández et al., 2021). For engineer-to-order products to be successfully developed with the help of this type of automated design, the tools and methods used must be efficient and utilized through the entire development process (Amadori et al., 2012).

Method

The research was conducted as a case-study at one of Sweden's largest IHB companies. The case study included empirical data collection and qualitative analysis of three different product brands at the company: Brand 1, Brand 2 and Brand 3, which are differentiated by the building systems used and the target market segments. Both Brand 2 and Brand 3 are prefabricated using building systems based on volumetric elements, where Brand 2 is a single-family housing brand and Brand 3 is a multi-family housing brand. Both Brand 2 and Brand 3 are produced in the same factory, however, have separate assembly lines. Brand 1 is a single-family housing brand prefabricated using a building system based on panelized elements. These elements are produced in another factory. The company continuously develops pre-engineered design solutions and house types for each brand which both take place apart from the customer orders. On the other hand, by developing specific design solutions towards the orders, the company realizes its single-family houses for end-customer. Brand 3 is developed as a project for professional customer orders. The company engages in project development also by acquisition of land and creating new housing areas by configuring and filling the land with various products from all three brands.

Fourteen respondents were interviewed to collect empirical data. A range of relevant roles and disciplines were covered by the interviews: three product managers, two production technicians, two project developers, CAD development engineer, product concept developer, fire safety specialist, structural engineer, architectural designer, technical manager, and the chief architect. The interviews were semi-structured with follow up questions to allow respondents to elaborate on structure and content of the design and production processes they have knowledge of and what they would require from a generative design application. The respondents were asked to describe their responsibilities within the design and production processes, the requirements they need to meet, how they use digital tools, and what the challenges and potential improvements are regarding digitalization. Apart from answering these questions, technical manager provided description of building systems and platform flexibility in each product brand.

Results

Empirical findings are first divided into digitalization and BIM interoperability, and platform flexibility. The section is concluded with the respondents' replies and inputs on generative design.

Digitalization and BIM interoperability

The software used at the company includes 3D CAD and 2D CAD modelling, CAM and CAE tools and ERP system. Moreover, a generative design tool is available as part of the 3D CAD modelling software. There is a shared opinion among the respondents that the capabilities of the digital tools used at the company are not being fully utilized. BIM development engineer described it as 'halfway' digitalization, where they develop 3D CAD models but still need to produce 2D drawings, and PDFs are still used as a main information carrier in the production. This, in turn, leads to a considerable amount of repetitive work, and project managers and architectural designer mentioned that they often must manually copy information between models and documents. There are guidelines on how to work in 3D CAD and 2D CAD modelling software, but no clear guidelines on how to handle, store, and share digital information in general are being followed. The respondents working with these types of software share the opinion that the main problem is not having an integrated BIM system in which they can work, store, and update all models and information. This in turn, leads to manual information transfer and multiple manual updates of models and documents, due to everyone not working in the same models or documents. The respondents added that if not everyone works in the same way it expands the room for errors. Architectural designer also "wished" for more data to be put into the CAD tools, to facilitate the development process at an earlier stage. An often-occurring issue is a long chain of communication through emails before the relevant person with needed expertise is reached, and no appointed responsibilities are delegated to take care of respective tasks. BIM development engineer specifically addressed this problem as a need for more cooperation in digitalization, and that it is also difficult to push through or implement changes in the way that the company works with digitalization. As pointed out in the interviews, not all problems related to digitalization and BIM interoperability are internal. The company also relies on external consultants for the dimensioning of mechanical, electrical, and plumbing (MEP) systems, but they do not put any demands on the models or documents produced by these consultants. Consequently, the consultants' drawings and data must be manually copied into their own models. The structural engineer stated that some of these tasks could have been completed by own resources given necessary software was available.

As new products are developed and existing products are adjusted, these changes must also be within the solution space of building systems. The production technicians both said that visualization of the production lines is helpful when planning these changes, especially when discussing the changes with the production staff. However, not everyone seems to agree with this view, as they also said that not everyone sees the benefits of digitalization. The production technicians also have the same opinion that a tool that could help compare solutions would be helpful. The aspects most interesting to compare for this use would be costs, throughput times and logistics flows. However, this data first needs to be collected, which is something that they currently do not do. One of the production technicians said that there is no continuous work for improvement, as they do not measure production times or put demands on themselves.

The company has a database with all currently released pre-engineered house models. This database is continuously updated as products are introduced or phased out. They also make sure not to introduce too many new products, as this creates even more variance in the already complicated design stage. The company also has guidelines on how to design products that fit within the building system.

Platform flexibility

Depending on the brand, the products are built using building systems based on either panelized or volumetric elements. Panelized elements could, for example, be walls or floors with partially completed electrical installations, while volumetric elements are entire rooms or parts of an apartment building or chain house with completed MEP systems and most of the interior done as well. Panelized elements provide more design freedom for the architects as the off-site manufacturing systems they are produced at are assembly lines which have the flexibility in terms of lengths and the placement of openings for the exterior and interior walls, and length and width for the floor cassettes. Moreover, roof trusses can be efficiently manufactured in a variety of sizes and roof angles. The floor plans of these products, which is Brand 1, can vary to a great extent and are more steered by customer requirements and legal requirements such as accessibility. Hence, the products of Brand 1 are mostly developed only when there is a client order.

Unlike the panelized elements, the volumetric elements provide much less design freedom and much more consideration as the MEP systems are prefabricated as well, and because there are transportation limitations. Volumetric elements together can form chain houses, apartment buildings (Brand 3) or a single-family house (Brand 2). Because of this, the different elements have different production flexibility in different areas. Since the volumetric elements are made up of panelized elements as sub-components, the walls can be produced at the same assembly lines as in the case of Brand 1. However, despite the flexibility at the assembly lines, only a limited number of pre-engineered wall types are produced, since there are eighteen pre-engineered house models where some wall elements are shared. In the case of the floor elements for Brand 2 and Brand 3, separate assembly lines are used, and the variation is limited due to the integrated designs of MEP and structural systems. The volumetric elements, therefore, allow limited flexibility where customers can make choices regarding the interior design and the type of façade since these do not affect the production as much as a change in the floor plan can. Hence, pre-engineering for Brand 2 is on the level of the whole product. The eighteen pre-engineered Brand 2 single-family house models are built using volumetric elements for the first floor, and in the case of one and a half and two-story houses, the second floor is built with panelized elements, making it a hybrid structure between panelized and volumetric elements. The volumetric elements are also used in Brand 3 products to create apartment buildings with multiple floors. Due to the design of the volumetric modules, these apartment buildings and chain houses also have some rules on how they can be put together. Moreover, there are standardized modules for stairwells.

The development of specific design solutions is the process initiated for specific orders where pre-engineered solutions are configured into unique products. It could either be to develop a Brand 1 single-family house for a private customer or develop a larger neighborhood for a professional client order by populating it with products of all three brands. These larger projects could either be acquired through a contract with a municipality or on a property procured by the company themselves. As the designs of the pre-engineered modules and products are not changed, but instead, it is about their configuration into whole areas, the efficiency of the off-site manufacturing systems is not negatively affected.

The emerging new product technologies, frequent updates of building codes and regulations, are continuous challenges the company must face as they affect building systems and off-site manufacturing systems. The changes require finding optimum solutions, and in most cases, the solution will be a compromise between different conflicting goals, with the legal requirements as the baseline. Product managers, technical managers, and structural engineers share the opinion that it would be easier to make these compromises if they had a way to easily compare solutions. Moreover, it would be beneficial to be able to make decisions faster and earlier while still ensuring that all parameters are included, and all requirements are fulfilled.

According to the project managers, the main problems with designing specific design solutions are the local contingencies, local legal requirements, and customer requirements. Moreover, parameters such as land use and municipality requirements occur often. Because of this, the respondents said that a way to compare solutions would be beneficial for project design as well. The development of entire neighborhoods takes a lot of time, and some respondents believed that projects using products based on volumetric elements had the largest potential for an improved and more efficient process. For example, if the initially designed solution did not pass the building permit, the design process of a new solution had to begin from scratch. There are also ownership uncertainties with projects since project developers own their projects, but who is responsible for various parts of the project is still unclear. Another major issue for project developers is the lack of information available in the early stages of the project. They particularly mentioned prices and information on available products as the two main culprits here. Project developers especially wanted to get an indication of the project's price earlier in the process, as this is something that currently must be calculated manually for every solution. It is also stated that it would be beneficial to be able to lock in some choices earlier in the process while still allowing for variation.

Generative design

When asked about generative design, eight respondents indicated that they had never heard of it before. Of the remaining respondents, three people reported familiarity with generative design and its capabilities. Some of the respondents who knew about generative design before this study gave specific examples of its potential benefits for the company. These included assistance with assembling volumetric modules that meet all structural requirements, especially for use in larger, taller buildings, as well as support when preparing off-site manufacturing systems and supply chains. A few respondents were concerned that the preparation needed to develop a generative design model would take more time than they would gain from the solution. Some individuals, including the chief architect and architectural designer, were also concerned that "soft" values would be lost or difficult to incorporate into a generative design model. The chief architect advocated for using the method only to visualize how volumetric elements can be assembled, as these elements are already designed.

Discussion

While the interviewed respondents are in general satisfied with their digital tools, their main concerns relate to the issues surrounding digital information sharing and availability of data earlier in the design process which is partly a consequence of lacking a fully integrated BIM system. This supports Bianconi et al. (2019) findings that BIM interoperability can help increase level of detail in the early stages. The lack of information in the early stages of the design process also limits the potential for everyone to have knowledge about the project, leading to a wide information spread, with many people only knowing things specific to their own work. This was pointed out by the structural engineer, and the solution to this problem lies in, according to Lessing (2006), good communication and organizational relationships.

This lack of information in the early stages of the design process can also prevent the company from taking advantage of generative design due to the complexity of multi-criteria design, as according to Hernández et al. (2021), this requires a lot of in-depth knowledge about the problem. The company therefore needs to ensure that the necessary information is available earlier in the process before adopting any generative design solution if they want to enjoy all the benefits it can provide. All the respondents that are involved in the development of house models said that acquiring this information earlier is possible, it is just that it must be done manually for every project or product. This is where an integrated BIM system could again prove helpful, as continually updated models with integrated data about measurements, prices and materials could provide designers and managers with such information, without having to redo manual checks and calculations every time.

As the flexibility among three platforms vary, therefore, according to Monizza et al. (2018) does the potential use of generative design applications. As Brand 1 products have higher flexibility due to the panelized elements building system, generative design applications can be used both when developing pre-engineered and specific design solutions. These might therefore include: floor plan studies (Hu et al., 2020, Zhang et al., 2021), sustainability checking (McGlashan et al., 2021), optimization of costs based on structural design (Hernández et al., 2021) and optimization of production times of panelized elements (Liu et al., 2021).

In case of Brand 2 products, due to the volumetric elements building system, flexibility of the platform is limited, and generative design applications are meaningless when developing specific design solutions for private customers. The use of generative design applications in developing pre-engineered design solutions might be too complex for Brand 2 products due to the large number of requirements that have to be considered simultaneously. It also might not justify the investment in developing generative design models (Chang et al., 2019), as typically only two to three volumetric elements constitute a house in this product brand.

On the other hand, in case of Brand 3 products, multi-family buildings can be made up of many volumetric elements so the use of generative design applications such as evaluating energy building performance (Caldas, 2008) and optimization of costs based on structural design (Hernández et al., 2021) might be justifiable. Moreover, project development could benefit from more generative design applications such as planning of neighborhoods (Nagy et al., 2018), optimization of the construction site planning (Mohammed Fathy et al., 2022) as the complete product in such projects is most commonly not a single building but sometimes multiple buildings in combination with single-family houses combined.

While this study only covers the situation at one company, Lessing (2006) shows that there are several commonalities between different IHB companies, like their business models based on product platforms and structure for standardized, repetitive processes. This means that parts of the analysis in this paper are generalizable, however other companies are likely to be at various levels of digitalization and have different digital tools available, meaning the generative design uses available to different companies might differ.

Conclusions

The aim of this research is to identify the current level of digitalization, BIM interoperability, and platform flexibility present in IHB as prerequisites for generative design applications. The results show that the current state of digitalization and BIM operability can impede the use of generative design applications in the design processes of all three product brands at the company. The lack of an integrated BIM system hinders digital information sharing and the availability of data earlier in the design process, which can prevent the company from taking advantage of generative design applications. The flexibility of a single-family housing platform based on panelized elements and a multi-family housing platform based on volumetric elements is suitable for the potential use of generative design applications. Generative design applications, such as floor plan studies, sustainability checking, optimization of costs based on structural design, and optimization of production times of panelized elements, are possible both in the development of pre-engineered and specific design solutions of single-family housing built in panelized elements. In the case of project development for professional customers, where the company develops whole neighborhoods by combining multi-family housing built in volumetric elements with single-family housing built in both panelized and volumetric elements, generative design applications, such as planning of neighborhoods, optimization of the construction site planning, evaluating energy building performance, and optimization of costs based on structural design, might be used.

Future research on generative design applications in an IHB context might include further investigation on the amount of preparation each specific application might require, as well as the impact it might have on the design processes and their priority for implementation. Moreover, the suggested future work includes how to use generative design to perform various tasks and how to set up these models.

generative design to perform various tasks and how to set up these models.

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