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APPLYING A DFMA APPROACH IN THE REDESIGN OF STEEL BRACKET -A CASE STUDY IN POST AND BEAM SYSTEM

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ABSTRACT

Design for manufacturing and assembly (DfMA) has gained increased attention in the construction industry as the process has been industrialized and shifting towards a combination of factory prefabrication and assembly on site. The aim of this study is two-fold. Firstly, to apply the DfMA approach in the redesign of a steel bracket from a post and beam building system to simplify the design for reducing the cost and improving manufacturability. Secondly, to experimentally evaluate the mechanical properties of the redesigned bracket for implementation. An experimental case study has been conducted in a multistorey post and beam building system. The empirical data were collected from five semi-structured interviews and two workshops.

The result shows that the DfMA approach has the potential to improve the manufacturability and cost of building components in Industrialized house building (IHB) and is comparable to lean design. Moreover, the proposed steel bracket offers satisfactory load-bearing capacities and shows an improvement with a reduction of cost by 15%, lead time by 50%, and material efficiency by 25%. DFMA can be used as a promising approach for aligning the design phases of IHB with the production and assembly by improving cross-functional collaboration.

KEYWORDS

Off-site construction, Design management, design for manufacturing, design for assembly, lean construction.

INTRODUCTION

IHB companies are challenged to improve their productivity as the demand for housing in the market has increased dramatically (Uusitalo & Lavikka, 2021). The companies must be able to respond quickly to changing market demands and unique customer requirements (Grenzfurtner et al., 2021). This has triggered them to consider means to improve the cost and lead times in both design development and production process to

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become competitive in the housing market (Jansson et al., 2014). The design phase contributes significantly to the performance of a project and has been considered the crucial stage of the IHB life cycle with uncertainties and iterations (Lidelöw & Jansson, 2017). Besides, the design phase is the most suitable stage in the whole life cycle of an IHB project to establish new solutions that can have a high impact (Vaz-Serra et al., 2021). The knowledge exchange between design and production leads to continuous improvement (Gao et al., 2020; Lessing & Brege, 2015). Thus, placing more consideration on production knowledge early in the process is a proven strategy to reduce cost and bring efficiency.

The post and beam system is one of the oldest building systems built mostly on concrete and steel but has been using timber structures in the past decades (Tlustochowicz, 2011). Steel brackets are used to connect the post and beam where brackets are a key component of the building system due to their custom-oriented nature (Thajudeen et al., 2018). The production of customised building components generates several new knowledge and experiences, and it is important to integrate those into the design process (Gerth et al., 2013; Tillmann et al., 2015). There are several approaches by which the design phase of IHB can be efficient, thereby improving the overall productivity (Grenzfurtner et al., 2021). One way to improve the IHB design is by adopting an integrated method supporting the decision-making process for designers.

The Design for Manufacturing and Assembly (DfMA) approach has been widely used for decades in several industries for the development and rationalizing of products, such as the aerospace, automotive other manufacturing industries (Vaz-Serra et al., 2021). The potential of the DfMA approach has increased by industrialising the construction activities where the building components are manufactured in the factory (Tan et al., 2020). The design for manufacturing (DFM) and design for assembly (DFA) concepts are more essential than ever in the IHB industry (Tan et al., 2020), particularly for companies offering customised buildings (Yuan et al., 2018). The implementation of DfA and DfM has the potential to bring considerable benefits, including reducing costs for manufacturing and assembly, enhancing product quality, and shortening production time by simplifying products (Boothroyd et al., 2010; Lu et al., 2021).

Several researchers have studied the possibilities of incorporating DfMA in the IHB process and provided an overview of the application at the industry level (Gao et al., 2020; Langston & Zhang, 2021). This is evident from the literature review on DfMA and its application in prefabricated construction by Wasim et al. (2020) where most studies are performed in recent years. However, existing practices in construction generally follow the DfMA approaches established in a manufacturing setting without sufficiently considering the critical aspects of IHB (Lu et al., 2021). Moreover, demonstration of the practical application of DfMA approaches in IHB is limited (Tan et al., 2020) and no studies have been performed in the post and beam IHB system. Therefore, the aim of this study is two-fold. Firstly, to apply the DfMA approach in the redesign of a steel bracket from a post and beam building system to simplify the design for reducing the cost and improving manufacturability. Secondly, to experimentally evaluate the mechanical properties of the redesigned bracket for implementation.

THEORETICAL BACKGROUND

IHB involves the prefabrication of components and modules in factory settings and the efficient use of technical systems and components with different levels of standardization, that are combined to form unique buildings (Lessing & Brege, 2015). The management of IHB design is crucial as it involves either modifying existing solutions according to new requirements, configuring a product's modules or designing a new version of a product (Thajudeen et al., 2018). The design phase of IHB plays a crucial role in determining the resources, costs, time and others for the production and assembly process. Ensuring improved quality and minimizing the production cost is key to an optimised design (Ulrich and Eppinger, 2008). One way to evaluate the design of a product is with the DfMA approach (Wasim, 2020).

DfMA is a design philosophy and method that originated in the manufacturing industry (Tan et al., 2020). It consists of two parts where DfM is mainly concerned with the enhancements in the manufacturing of individual parts and DfA addresses the means of assembling them efficiently (Bogue, 2012). DfMA strategies have evolved from the manufacturing industry and are widely used to improve productivity in construction with the primary aim of optimising the cost, quality, and lead time (Lu et al., 2021). The typical stages of the DfMA approach presented by Boothroyd (2005) have been used for this study. According to the author, DfA should consider in the beginning, leading to a simplification of the product structure. The economical selection of materials and processes and early cost estimates is the next step to comparing the cost and material utilisation of old and new designs. This is followed by the analysis of DfM aspects to reduce total manufacturing costs and operations involved.

Lean construction is a method which adapts the concept of lean production to maximize the value-adding activities and minimize waste (Koskela, 1992). The principles of lean construction and DfMA are interrelated and mutually supportive (Lu et al., 2021). Several methods and tools such as the last planner system, target value design, set-based design, and design structure matrix have been introduced to support lean application (Uusitalo et al., 2017). Design management methods such as lean design, last planner in design and agile management in construction have been discussed by Lidelöw & Jansson (2017). Lean construction and DfMA share the same principles as both ensure improved product quality while minimizing waste and manufacturing costs (Gerth et al.,2013). They introduced an approach named Design for Construction (DfC) based on DfMA and shows the importance of experience feedback in the design phase for enhancing productivity. Ng & Hall, (2019) identified the common practices shared to demonstrate their potential synergies of them in the construction industry. As dominant factors of DfMA adoption, they identified just-in-time, reduction of speed and improvement of site management and concurrent engineering (CE) from a lean perspective. However, these two principles are viewed differently where lean aims to eliminate construction waste and DFMA works on improving ease of manufacturing and assembly from the early stage of design (Gao et al., 2020).

The production knowledge supports the designers to evaluate product characteristics (Gao et al., 2020). Tillmann et al (2015) investigated the topic of managing the production of custom components on a complex project and discussed the importance of integration of design and production. By considering the downstream processes of manufacturing and assembly, DfMA offers a method for evaluating and improving product design (Boothroyd et al.,2010; Lu et al., 2021). Here, the optimisation achieved through DfMA at the early design phase can substantially contribute to best practices, reduce time and delays, improve safety, and thereby enhance the overall productivity of the prefabricated construction project (Wasim, 2020).

Over the last few decades, several studies have highlighted the importance of DfMA in the design stage, presenting different approaches to facilitate improvement. However, there is a lack of practical studies in the IHB sector showing how companies can benefit from the DfMA approach. The literature reviews show that the traditional approach is still used in construction and there is a need to develop affordable technologies for better adopting DfMA strategies for the IHB industry to improve efficiency (Langston & Zhang, 2021). Moreover, a coherent description of DfMA specifically for IHB is needed for successful development. By acknowledging the current gap, this paper intends to demonstrate the adoption of the DfMA approach in the house building industry.

RESEARCH METHODOLOGY

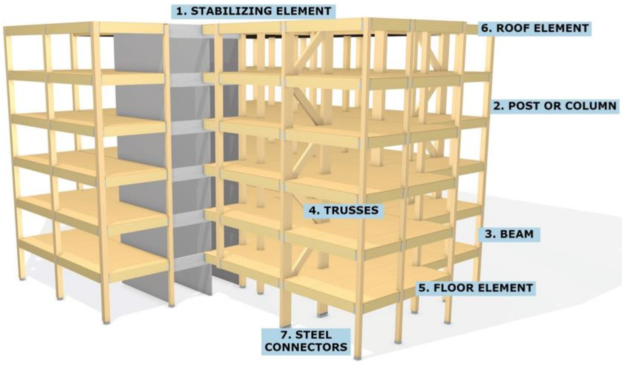
An experimental case study has been conducted in a Swedish company offering multistorey buildings using the post and beam system (Karlsson, 2016). A case study method allows to focus on a particular issue within a real-life context and is often jointly used with other qualitative methods to enhance robustness (Yin, 2018). The primary data for this study has been collected from multiple sources by triangulating methods such as workshops, in-depth interviews, document analysis and literature reviews. The unit of analysis was the design and manufacturing process of steel brackets in the building system, which is a suitable case from the DfMA perspective. Empirical data were gathered from two workshops and five semi-structured interviews by including experienced participants from the case company and supplier of the bracket. The participants were: the design manager, senior structural engineer, CAD engineer, structural engineer, and production engineer from the supplier. The selection was based on their experience in bracket design and knowledge about the production process. The questions were mainly focused on the challenges in the existing component design from a process perspective and the opportunities of the bracket redesign from a DFMA perspective.

A review of DfMA approaches was conducted as the first step to understanding key concepts and practical applications in construction and more specifically in IHB. The different stages of the DfMA approach presented by Boothroyd et al. (2010), have been followed and used for analyzing the study. DFMA approach has been chosen for redesigning the bracket as the production and assembly aspects were significant for this study. The knowledge of the design and production process of steel brackets gathered from workshops and interviews were mapped and related to the DfMA approach. The first workshop focused on the existing old design and its challenges whereas the second one aimed at the new design, its benefits and evaluation to implement in projects. The suggestions for improving the current design of the bracket were taken into consideration.

The work has been carried out in close collaboration with the supplier of steel brackets. A factory visit to the supplier was undertaken to deepen the understanding of how components are produced and create a process map for analysis. This mapping aided to compare the lead time for the old design and the new design of the bracket while the prototype was produced during the visit. Moreover, document analysis for three previously finished projects was conducted including detailed drawings of brackets, assembly drawings, BOM list, and invoices for performing the cost analysis. The prototype fabricated with the new design has been tested at the test rig located at the case company with the support of structural engineers from the case company. This was mainly to analyse the mechanical behaviour of brackets as part of the evaluation and to support the final decision for implementation in future projects. Finally, the collected empirical data including the experimental findings have been analysed using the procedures recommended by Miles et al., (2014) and reported.

CASE STUDY

A leading manufacturer of Glulam (Glued laminated wood) based multistorey house building system to the Swedish market has been selected as the case company. The building system is named Trä 8 which means that it can be used for up to eight meters of free span enabling flexibility for architectural designs. The fundamental part of the system is the idea of "Big Size Pre-Cut", where a high level of prefabrication of large building components and sets of material is developed through efficient production. The main components of the building system and the assembly view of the steel bracket are shown in figure 1.



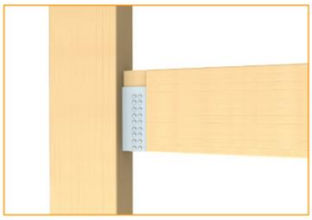


Figure 1: Trä 8 building system and assembly view of steel bracket

REDESIGN OF STEEL BRACKET

In a post and beam building system, vertical post and horizontal beams are connected to form a structural frame where steel connections play a vital role in structural stability when subjected to lateral loadings (Thajudeen et al., 2018). Steel brackets are engineered components used to transfer loads from the beam (secondary member) to the post (primary member). In the Trä 8 system, brackets are designed to transfer different magnitudes of loads from several floors to the foundation through the vertical post.

The load transmission between the secondary and the brackets takes place mainly by contact pressure, while the load transmission between the brackets and the primary beam takes place by means of nails, through screws. Moreover, by transferring the horizontal loads to the wooden trusses, they function as stabilizing elements for the building. They are folded from a piece of sheet metal "S355J0" with a required thickness of 5mm, screwed to the members with 8mm screws. The variety of the brackets depends on the size of the beam, the number of screws in the primary & secondary objects and the required load capacity. This generates an increased number of variants after every project. Thus, the reuse of brackets is limited creating difficulties in standardisation. Therefore, design support is essential for designers from a process perspective as a solution for managing the challenges due to the customization.

Design and production process of steel brackets

The findings from the production visit and interviews with the case company and suppliers are reported. The design process of steel brackets generally includes structural design, modelling and detailed drawings for production and assembly. The structural design identifies different types of loads acting on the building and the dimension of the primary and secondary members. Math CAD is used to design the brackets where the vertical load, horizontal load, the dimension of the beam and the size of screws that insert into the post are required for calculating the brackets. The following step is the modelling of the building and detailing of different variants of bracket components. Tekla structure is used as the tool for both modellings of building and detailing of components in 2D format for production and assembly. Finally, all these drawings and requirements are forwarded to the suppliers who produce the brackets.

The case company has long-term cooperation with the suppliers and has been involved in the development activities. The process mapping of old bracket production is shown in figure 2. The order from the case company includes the detailed drawings of brackets with all individual assembly details prepared by designers. These drawings are then prepared for production by the suppliers in a way that maximum yield can be achieved during the operation.

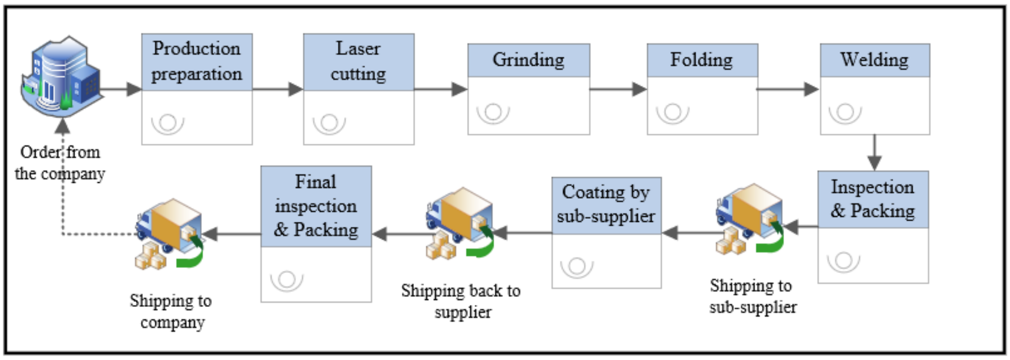


Figure 2: Process mapping of the old design

The first operation is cutting smaller sheet components from sheet metal into the necessary shapes and dimensions with the help of a laser cutting machine. The holes required for screws are also punched during this operation. The next step in the fabrication process is the grinding of sheet metals to smoothen the surfaces and edges. These smoothed components are then folded into a bracket. The following step is the welding of the bottom edges of these brackets. A random inspection and packing are carried out after the operations and transported to the sub-supplier for performing the electric galvanised coating on the bracket. This process usually takes a week, and the components will be shipped back to suppliers again. The final inspection and packing are performed before transporting the coated brackets to the company directly or building site depending on requirements. This is because brackets are welded at the site, in some projects where the coating needs to be done at the site.

There are several challenges involved in the production of old bracket which is important to consider while designing. The existing challenges were discussed in the first workshop. The most highlighted challenge of the old design was the lead time as it utilizes extended time with the process such as welding and galvanised coating on brackets by sub-suppliers. The process mapping shows that one and half weeks is required for the coating process from sub-suppliers. Moreover, the time requires for folding operation is high for the old design. The higher cost is another problem as it involves a lot of operations as shown in the figure. Moreover, this design uses more materials for the bottom part which is welded to the adjacent side. Here, the welding requires more time and energy which is not sustainable. Another challenge is that the old design generates a lot of scraps on the sheet metal from which the brackets are cut out. Any change in bracket size creates a lot of scraps when the sheet metal is prepared for production.

New design of bracket and its benefits

A new design and production process for the bracket is proposed as shown in figure 3. Here, the welding operation has been avoided by folding the bottom plates at the supplier level. Additionally, the coating operation by the sub-supplier including transportation is eliminated from the process. Therefore, the overall lead time can be reduced as the whole process has been reduced in half. The coating process can be avoided as the brackets are produced from pre-coated plates with magnelis which is a metallic coating that offers high corrosion resistance and protection against long-term wear. The time taken for folding operation is less for the new design. The new design is more sustainable as the energy can be saved by avoiding the welding operation and transportation can be reduced.

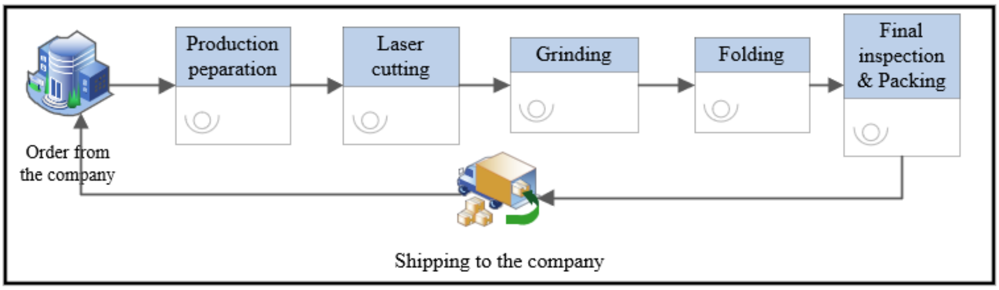


Figure 3: Process mapping of new design

As shown in figure 4, one advantage of the new design is the utilisation of material as the maximum number of brackets can be accommodated in the sheet metal depending on the size of the bracket. According to the production engineer, 25 folded type brackets can be produced from sheet metal whereas only 20 can be produced with an old design. The main reason is that the bottom neck part can be avoided which saves a quite amount of material. The tolerance generates when folding is manageable while tightening the screws. In other words, there is no need for the base plate as the screws can take the loads from the building. Yet the new design has this extra safety to support the load from the beam. The bottom plate is required during the assembly of beams as a support member. The advantage is that the brackets can be aligned in a different direction to reduce the scrap generated. The analysis shows about 25% of material efficiency when compared to the old design.

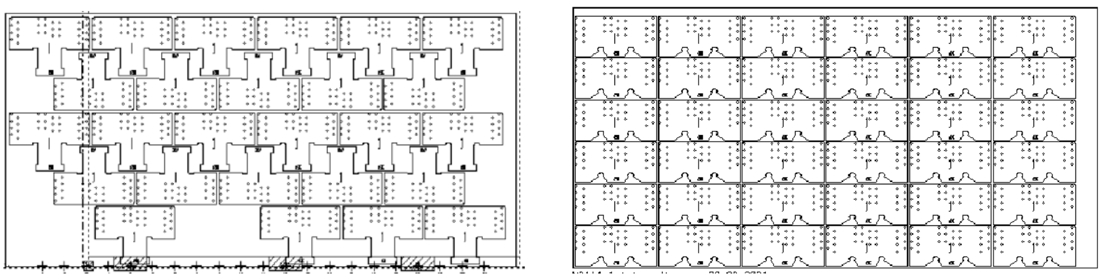


Figure 4: Process mapping of new design

Additionally, a cost comparison has been performed with brackets produced from old and new designs as shown in table 1. A document analysis of two previously completed projects was carried out. The total number of brackets produced including all variants used in these projects was taken to compare the cost. Table 1 shows the comparison between the cost of the new and old design. The analysis shows that the production cost can be reduced to 15 to 20% and this was also verified by the suppliers from interviews. Moreover, there is no additional investment needed for producing the new bracket as the operations are the same and few processes were omitted.

Table 1: Cost comparison of old and new brackets from selected projects

Project	Variants used	Numbers of brackets used	Total price with old design (SEK)	Total price with the new design (SEK)	Cost difference
Project 1	2	206	75850	64473	11377
Project 2	3	759	682736	580324	102412
Project 3	18	207	73521	62493	11028
				Cost-saving of 15%	

EXPERIMENTAL PROCEDURE AND ANALYSIS

As part of the evaluation, the newly designed bracket has been tested in the test rig located at the case company. The main purpose was to experimentally assess the behaviour and load-bearing capability of the newly designed steel bracket when subjected to dynamic loads. The test specimen includes a column and beam connected with a bracket and a hydraulic device that pulls down the specimen. The load on the bracket has been adjusted with the help of a hydraulic hand pump. Four draw wire type transducers were used for this experiment which accurately measure the position or change in position of members when applying the load. The transducers are connected to the workstation to observe the behaviour and to measure the load and deflection.

In total, there were two setups for testing the behaviour of brackets loaded from the vertical and horizontal directions. Three trials were performed from the first setup including the testing of one old and two new brackets for horizontal loads and two trials from the second setup with two new brackets on vertical loads. The conditions for failure were considered at the point of deformation of bracket or screws on primary and secondary or screw withdrawals.

The first setup is performed by placing the column and beam at an angle of 5 degrees. The load was increased uniformly, and screw withdrawal from the primary member occurred at the load of 54 KN for the first trial, 68.6 KN for the second trial and 69KN for the third trial. Here, similar deformation has been noticed on the steel brackets and screws from three trails where screw withdrawals were the reason for failure. The final breakdown occurred due to tension perpendicular to the grains of the primary member.

In the second setup, the testing was performed by only screwing the brackets to the column with a dimension of 165X225 mm. This setup was mainly to analyse the behaviour of the bracket under vertical load. Therefore, the secondary members were not screwed. Also, to verify the stability of the folded bottom part of the newly designed bracket. The post and beam connection is designed in such a way that the screws are load-bearing components holding the designed load after the assembly at the site. Here, the main purpose of the folded part was to hold the load from the beam before screwing.

The deformation in the bottom folded part has been observed with an increased load of 86 KN for the first trial and 96 KN for the second trial. The final failure of the bracket happened at the total load of 96 KN applied on the beam which is distributed to the two supports. However, the position of the applied load was close to the bracket where the most load was taken in this case. Therefore, the failure load is estimated to be 75.6 KN. The reason for the failure was due to the combination of crushing and tension perpendicular to the grains where the friction generated in the bracket damaged the folded part of the bracket. The measured load-mid-deflection behaviour of the specimen from setup 1 and setup 2 is shown in Figure 5.

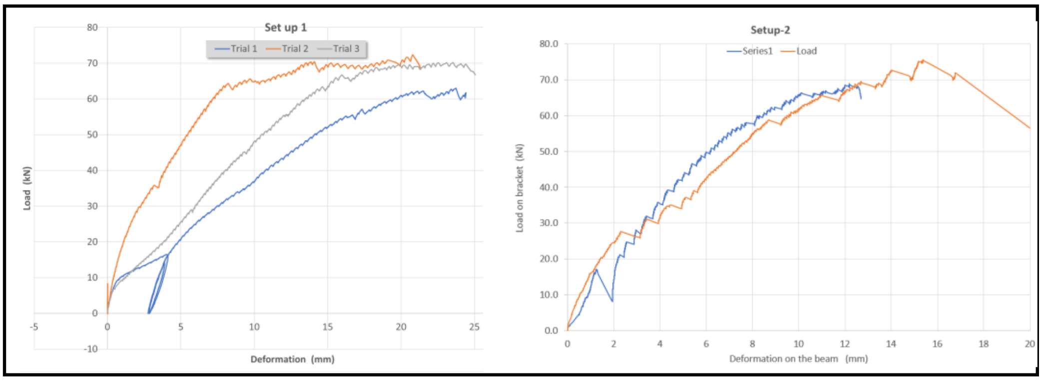


Figure 5: Load-deflection behaviour of the test specimens from setup 1 and setup 2.

DISCUSSION

This paper reports a case study of a successful application of DfMA in the redesign of a building component. The outcome of this study highlights the use and positioning of DFMA in the context of lean construction (Ng & Hall, 2019). IHB companies are generally following the same routine and use similar methods or tools where they put extended effort on sub optimising those to gain efficiency in the process. However, optimising these existing solutions might be a short-term goal. Another way to handle this situation could be to take a holistic approach and apply or test different methods and tools to achieve a long-term goal (Jansson et al., 2014). The lean principles are commonly applied to improve the production process although they can create value across the process from a holistic view. The point here to emphasise is to extend the process and include the lean way of working in the engineering design, thereby identifying value-adding activities in the whole chain (Lidelöw & Jansson, 2017).

From a process perspective, one remarkable finding is that DFMA can be considered as a method that can foster a lean culture in daily engineering work (Tan et al., 2020). Lean design can be used to standardise the process and optimise the whole process from quotation to the assembly at the site (Uusitalo et al., 2017). The opportunities for asset reuse have been increased in IHB, unlike traditional construction where standardisation of processes and components can be achieved with DFMA guidelines and checklist (Jansson et al., 2014). Here, DFMA complements lean design by providing relevant knowledge and experience from production and assembly available for designers in a set of predefined guidelines (Ulrich and Eppinger, 2008).

Another finding is that the term DFMA approach is not explicitly discussed in the lean construction community. However, several methods introduced as part of lean design share the same outcome. Applying DFMA can be a potential way to standardise the process of bracket design which promotes a lean design. The finding shows several improvements in the new design of bracket using the DfMA approach, resulting in significant cost savings and easy manufacturing due to a reduction in the number of parts and involved operations (Vaz-Serra et al., 2021). The results add value by reducing the waste in the process and indicating that DfMA and lean construction share common grounds (Gerth et al.,2013; Ng & Hall.,2019).

The steps presented by Boothroyd (2005) in the DFMA method have been followed in the redesign process and evaluation of the bracket. The finding from the study shows that this approach can be similarly followed in construction as in manufacturing to gain competitive advantages (Lu et al., 2021). However, some aspects need detailed descriptions and support in the IHB process. The method is mainly developed within other domains and the application area is mostly the manufacturing industry. In IHB, the assembly process has two parts i.e., component assembly at the site and assembly at the production facility. Therefore, DfA has to be classified into the design for assembly at the site (DfAs) and design for assembly at production (DfAp) and should be considered independently. Designers should be aware of the process and challenges of both stages. Here, assembly guidelines can be developed for both stages to support sufficient review and assessment of component variants available and how to use them, which also guides workers in the process (Bogue, 2012).

The study shows that companies are more familiar with management tools such as lean principles, agility, product platform etc. and are not fully aware of how to use the DfMA approach. This was evident from both the case company and supplier, where an explicitly defined or formalised method and guidelines were missing. However, the analyse of data shows that the companies are trying to design by making sure that components are easy to manufacture and assemble. DfMA aspects are considered a high priority during the design of components in IHB, and the designers are always considering aspects of the assembly process upfront in the process. However, the knowledge and experience from the production and assembly phase are not properly aligned with the design phase. According to the design engineer "*DfMA is something company should take into account as the study has resulted in getting a simpler and cheaper component design*".

The cross-functional collaboration to transfer gained knowledge from production and assembly and consistent information flow are necessary to implement DfMA and create it as a part of the company's culture (Gao et al., 2020; Tan et al., 2020). Documenting production and assembly knowledge is one of the most vital parts of company assets and the way to collect it and make it available for designers needs support methods and guidelines (Boothroyd et al.,2010). Hence, a good alignment can be achieved with production and assembly that provides an idea about what kind of asset can be built and used in different projects. There is a need for integrated support for designers and the analysis of empirical data put forward the possibilities for integrating a platform-based design approach to the traditional DfMA. However, detailed studies are required to show how this approach can be realized when dealing with components having different production strategies and can be considered a future study.

CONCLUSIONS

A novel beam-to-column connection with a steel bracket is proposed and experimentally tested the mechanical behaviour as part of the evaluation. The results show that the DfMA approach can be used as a promising tool for redesigning an existing building component and aligning the design phase of IHB with the production and assembly. Moreover, the contribution of this study to the IHB industry pointed to the importance of adopting DfMA as an integrated tool supporting decision-making for designers to facilitate lean design. Based on the analysis and experimental results, the following conclusions can be drawn:

- DfMA can be equated to lean principles in several aspects and has the potential in IHB to reduce waste and add value to the process.
- This study has resulted in an improvement in efficiency and the overall cost has been reduced to 15%, material efficiency by 25% and total delivery lead time of components by 50%. Moreover, the results of the experimental study indicate that the proposed steel bracket offers satisfactory stiffness and load-carrying capacities.
- In the IHB sector, the DFA has to be considered and evaluated separately, i.e., DFA for site and DFA for production.

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REFERENCES

Bogue, R. (2012). Design for manufacture and assembly: background, capabilities and applications. Assembly Automation. https://doi.org/10.1108/01445151211212262.

Boothroyd, G. (2005). Assembly Automation and Product Design (2nd ed.). CRC Press. https://doi.org/10.1201/9781420027358.

Boothroyd, G., Dewhurst, P., & Knight, W. A. (2010). Product Design for Manufacture and Assembly (3rd ed.). CRC Press. https://doi.org/10.1201/9781420089288.

Gao, S., Jin, R., & Lu, W. (2020). Design for manufacture and assembly in construction: a review. Building Research & Information, 48(5), 538–550, https://doi.org/10.1080/09613218.2019.1660608.

Gerth, R., Boqvist, A., Bjelkemyr, M., & Lindberg, B. (2013). Design for construction: utilizing production experiences in development. Construction Management and Economics, 31(2), 135–150. https://doi.org/10.1080/01446193.2012.756142

Grenzfurtner, W., Rudberg, M., Loike, K., Mayrhofer, R., & Gronalt, M. (2021). Industrialized housebuilding business strategies and the design of performance management systems. Production Planning & Control, 1–14. https://doi.org/10.1080/09537287.2021.1992030.

Jansson, G., Johnsson, H., & Engström, D. (2014). Platform use in systems building. Construction Management and Economics, 32(1–2), 70–82. https://doi.org/10.1080/01446193.2013.793376.

Karlsson, C. (2016) Research methods for operations management. Routledge.

Koskela, L. (1992). Application of the new production philosophy to construction (Vol. 72). Stanford: Stanford University

Langston, C., & Zhang, W. (2021). DfMA: Towards an Integrated Strategy for a More Productive and Sustainable Construction Industry in Australia. Sustainability, 13(16), 9219. https://doi.org/10.3390/su13169219.

Lessing, J., & Brege, S. (2015). Business models for product-oriented house-building companies – experience from two Swedish case studies. Construction Innovation, 15(4), 449–472. https://doi.org/10.1108/CI-02-2015-0009.

Lidelöw, H., & Jansson, G. (2017). The effect of pre-engineering on design management methods. 25th Annual Conference of the International Group for Lean Construction, IGLC 2017, Hersonissos, Crete, Greece, 9-12 July 2017, 523–530.

Lu, W., Tan, T., Xu, J., Wang, J., Chen, K., Gao, S., & Xue, F. (2021). Design for manufacture and assembly (DfMA) in construction: The old and the new. Architectural Engineering and Design Management, 17(1–2), 77–91. https://doi.org/10.1080/17452007.2020.1768505

M.B. Miles, A.M. Huberman, J. Saldaña, Qualitative data analysis: A methods sourcebook. 3rd, Ed Thousand Oaks, CA Sage. (2014), (ISBN).

Ng, M. S., & Hall, D. M. (2019). Toward lean management for digital fabrication: A review of the shared practices of lean, DfMA and dfab. Proceedings of the 27th Annual Conference of the International Group for Lean Construction (IGLC), Dublin, Ireland, pp.725-736. https://doi.org/10.24928/2019/0204.

Tan, T., Lu, W., Tan, G., Xue, F., Chen, K., Xu, J., Wang, J., & Gao, S. (2020). Construction-oriented design for manufacture and assembly guidelines. Journal of Construction Engineering and Management, 146(8), 4020085.

Thajudeen, S., Lennartsson, M. and Elgh, F. (2018) Impact on the Design Phase of Industrial Housing When Applying a Product Platform Approach. Proceedings of the 26th Annual Conference of the International Group for Lean Construction, 18-20 July, Chennai, India (pp. 527-537). DOI: 10.24928/2018/0281.

Tillmann, P. , Viana, D. , Sargent, Z. , Tommelein, I. & Formoso, C. 2015, 'BIM and Lean in the Design-Production Interface of ETO Components in Complex Projects. In Proceedings of the 23rd Annual Conference of the International Group for Lean Construction. Perth, Australia, 29-31 Jul 2015. pp 331-340.

Tlustochowicz, G. (2011). Stabilising system for multi-storey beam and post timber buildings. Luleå tekniska universitet.

Ulrich, K. and Eppinger, S. (2008) Product Design and Development, McGraw-Hill, New York.

Uusitalo, P., & Lavikka, R. (2021). Technology transfer in the construction industry. The Journal of Technology Transfer, 46(5), 1291–1320. https://doi.org/10.1007/s10961-020-09820-7

Uusitalo, P., Olivieri, H., Seppänen, O., Pikas, E. and Peltokorpi, A., 2017, July. Review of lean design management: processes, methods and technologies. In Proceedings of the 25th annual conference of the international group for lean construction, Heraklion, Greece, 9-12 Jul 2017. pp 571-578. DOI:10.24928/2017/0224

Vaz-Serra, P., Wasim, M., & Egglestone, S. (2021). Design for manufacture and assembly: A case study for a prefabricated bathroom wet wall panel. Journal of Building Engineering, 44, 102849. https://doi.org/10.1016/j.jobe.2021.102849.

Wasim, M., Vaz Serra, P., & Ngo, T. D. (2020). Design for manufacturing and assembly for sustainable, quick and cost-effective prefabricated construction–a review. International Journal of Construction Management, 1–9. https://doi.org/10.1080/15623599.2020.1837720

Yin, R. K. (2018). Case study research and applications. Sage.