Implementation of Design for Manufacture and Assembly (DfMA) principles in Construction: A Case Study

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ABSTRACT

Design for Manufacture and Assembly (DfMA) has been increasingly advocated by the global construction industry since it provides methodological procedures for evaluating and improving design for both manufacture and assembly. Many studies have investigated the DfMA principles suitable for different types of construction projects and advocated a wide implementation of DfMA in construction. However, it would be difficult to persuade stakeholders to implement DfMA principles in their projects without a clear specification of implementation procedures. This study aims to offer an intelligible description and analysis of implementation procedures of DfMA in a real construction project. It does so by undertaking a case study on a prefabricated bamboo building, in which a DfMA-focused design was required by the client. The study reveals how the knowledge of designer, engineer, and contractor has been integrated to implement DfMA principles in the design of building components and sub-components. This study also identifies the best practice of ensuring engineering performance and meanwhile attaining aesthetics in the application of DfMA principles.

INTRODUCTION

Growing demand for improving the productivity and quality of construction projects has attained attention from both the academia and industry. Apart from the improvement of construction technologies and workmanship in the construction phase, many researchers suggested that improvements should also be made in the design phase by considering more on the construction work. Gerth et al. (2013), for example, identified that insufficient feedback from onsite experiences to the design phase is one of the obstacles for improving the project productivity. Under this backdrop, Design for Manufacture and Assembly (DfMA), which is originated from the manufacturing industry, becomes a promising approach to enabling an integrated design process. DfMA has two components, i.e., design for manufacture (DfM) and design for assembly (DfA). Both components are more or less related to emerging concepts like off-site prefabrication and modular construction.

DfMA has been advocated by the global construction industry. Laing O'Rourke suggested that DfMA should be adopted in future construction projects to reduce costs of manufacturing and assembly and to quantify improvements (Laing O'Rourke, 2013). A DfMA overlay to the Royal Institute of British Architects (RIBA) Plan of Work 2013 was published in 2016 (RIBA, 2016). Various DfMA principles also have been introduced in the official documents of many other countries and districts, such as the "BIM for DfMA Essential Guide" of Singapore (Building and Construction Authority, 2016), "Construction 2.0" of Hong Kong (Development Bureau, 2018), and the "Analysis of the National Infrastructure and Construction Pipeline" of the UK (Infrastructure and Projects Authority, 2018). In addition, many researchers have reported benefits of DfMA implementation in construction projects (e.g., Fox et al., 2002; Gerth et al., 2013; Chen and Lu, 2018; Yuan et al., 2018). For example, the use of DfMA can encourage design integration and shorten construction time (Chen and Lu, 2018).

However, the application of DfMA in construction projects has been either sporadic or partially. Unlike the manufacturing industry where the standardized repetitive production processes allow the generic production knowledge to be easily shared with the design engineers, the construction industry has been characterized by its fragmented and one-off nature (Love and Gunasekaran, 1997). Stakeholders of a construction project generally focus on their own work and have less experience in knowledge sharing between different disciplines (Dave and Koskela, 2009). Without formal procedures of integrating construction knowledge into the design, the extent to which DfMA principles can be implemented in a construction project heavily relies on the varying capabilities of individuals.

This study aims to offer an intelligible description and analysis of implementation procedures of DfMA in a real construction project. The project is a prefabricated bamboo building that is designed according to DfMA principles. The knowledge integration process among the designer, the engineer, and the contractor for the building design is investigated with detail. Tools beneficial to DfMA implementation are also discussed. Findings of this study can help stakeholders to establish their own procedures of DfMA implementation so that benefits of DfMA can be harvested.

DESIGN FOR MANUFACTURE AND ASSEMBLY

The concept of DfMA can trace back to the weapon production in World War II. Formal approaches to implementing DfMA in industrial production were gradually developed in the late 1960s and early 1970s for design rationalization and material optimization. The increasing implementation of DfMA in the manufacturing industry has caused intense interest of researchers. Boothroyd (1996) suggested that DfMA provided a methodology for evaluating and improving product design by considering such downstream processes as manufacturing and assembly. Kuo et al. (2001) further explained that DfMA is the process of designing products to optimize the manufacturing functions, and to ensure minimized cost and maximized quality. Such an optimization process is like a feedback loop between the design and the production functions. In other words, the designers first develop the design, and the production engineers check whether the designed product can be efficiently produced with the current resources and workmanship (Hamidi and Farahmand, 2008). In addition, DfMA can fall into the business process stream, while both manufacturing and assembly processes will serve as the focal issues.

DfMA in construction

Although the vogue of DfMA in construction is only a recent phenomenon, the potential benefits of DfMA to construction projects have been recognized for over two decades (Anumba and Evbuomwan, 1997; Gao et al., 2018):

- Interactive participation in the design process by all stakeholders;
- Rapid implementation of design changes;
- Improvement in overall design integration;
- High-quality construction and reduced construction time;
- Minimum amount of manual labor;
- On-site wastage can be significantly decreased.

Some researchers doubted these potential benefits since the construction industry is of great heterogeneity compared with many other industries. The construction products (e.g., buildings and infrastructures) are usually bespoken by clients. It is thus extremely difficult for designers, like their counterparts in manufacturing, to ponder, optimize, prototype, and finally choose a design to build massively.

However, the construction industry has been reinventing itself and involving production theory (Koskela, 1992), especially by the integration of design, manufacture, and assembly. A few empirical studies have been conducted to investigate the implementation of different DfMA principles in the design of specific building components. For example, Gerth et al. (2013) reported the application of DfMA to the light wall design for two four-story houses. Kim et al. (2016) showed the DfMA application to selecting the precast beam of a highway bridge. Chen and Lu (2018) reported a case study of a high-rise commercial building, in which the curtain wall system was designed following a set of DfMA principles. Additionally, Banks et al. (2018) described the use of DfMA to support the design of façades, bathroom pods, and mechanical, electrical, and plumbing (MEP) elements.

CASE STUDY

The methodology of this research draws on Flyvbjerg's viewpoint of advancing the existing knowledge from case study (Flyvbjerg, 2006). An actual prefabricated bamboo building was selected as the case study project. Using a single case for case study might lack generalizability, but still has advantages in offering the "force of example" (Flyvbjerg, 2006). In view of the heterogeneous nature of construction projects, such a "force of example" can be particularly necessary for demystifying the underlying information in actual situations (Chen and Lu, 2019). Following Yin's

(2017) recommendations, data from different sources, including interviews and project archives, was collected in this case study project. The analysis of empirical data helps to reveal implementation procedures and impacts of DfMA in construction.

Description of the case study project

The investigated case study project is an alteration work in Hubei Province, China. The purpose of this project is to change the original building – a public service center – into a larger public facility for recreation and social activities. The original building was not designed following DfMA principles, and most of its components were demolished in this project. Then, the reconstructed public facility was designed following DfMA principles. Both design and construction of this project have been documented, providing sufficient information for evaluating the DfMA application and the impacts on the project accomplishment.

Implementation of DfMA principles

In this project, an interdisciplinary design team was formed, which included the designer, the structural engineer, and the contractor. The client required the construction work can be delivered as fast as possible, and in the meantime the construction of the proposed building should not generate much noise and waste to the surrounding environment. These requirements encouraged all design team members to collaborate with each other and apply DfMA principles to the building design. The overall project process is illustrated in Figure 1.

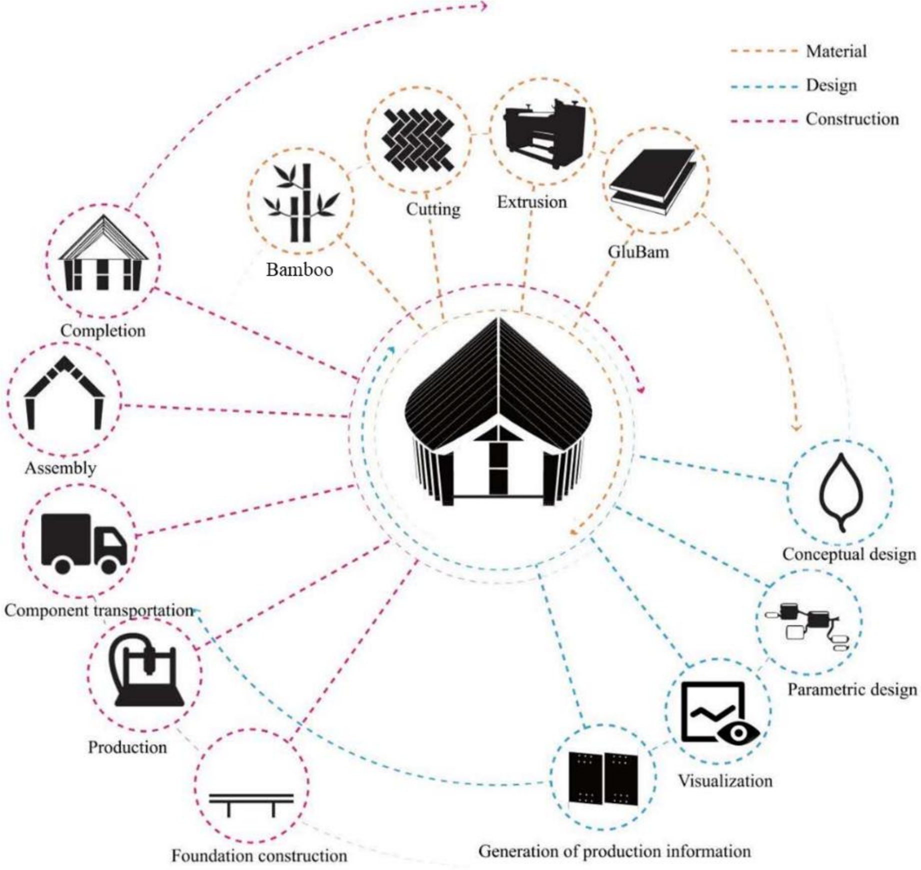

Figure 1. Overall design and construction processes of the case study project

At the initial stage, the designer proposed the conceptual design that the shape of the proposed building was like a leaf floating on the water. The designer also proposed the use of bamboo as the raw construction material for this building. Then, several on-site meetings were held for other design team members to discuss the feasibility of the proposed conceptual design and construction material. During the meetings, the conceptual design was confirmed by all design team members. Benefits of bamboo have also been identified. First, the use of bamboo can transfer cast-in-situ construction to off-site fabrication. Second, bamboo is a more sustainable raw material and has higher strength than ordinary wood. Specifically, the hardness of bamboo can be nearly 100 times that of ordinary wood, and the tensile strength is 1.5-2.0 times that of wood. Third, the bamboo has good physical thermal performance and has strong waterproof, anti-corrosion and alkali-proof performance. The early involvement of the structural engineer and contractor made their opinions available in the design phase. For example, the contractor suggested making use of some structural components of the original building in order to reduce the construction work as a whole.

Based on the conceptual design, the designer developed a detailed design with the knowledge contribution of other design team members. In this project, the detailed design was developed by using the computer-aided parametric design tool named Grasshopper. All team members reached agreement on the DfMA principles to be followed. First, each building component should be formed by as fewer sub-components as possible. Second, the size and shape of sub-components should be as identical as possible in order to grasp the advantages of mass production. Third, the sub-components should not be too heavy to allow on-site assembly. Forth, the connection of each two sub-components or components should be as simple as possible. Grasshopper helped to apply DfMA principles to design each component and sub-component.

The detailed design is an iterative process with continuous discussion among design team members. First, the parametric model, showing the overall building shape, was created in Grasshopper. The shape can be modified by changing the values of parameters. Then, the confirmed DfMA principles were converted into a set of rules (e.g., the length of every sub-components should not exceed 1600mm), and applied in Grasshopper to generate individual building components and sub-components. The generated components and sub-components were visualized in the user interface, and their parameters such as the size and coordinate were also presented to the design team. Therefore, both qualitative and quantitative analyses can be conducted to check whether the rules derived from DfMA principles have been followed. For example, the design team checked the number of different types of sub-components and analyzed whether the sub-components can be modified to be more identical. It is also worth noting that the designer has made extra effort to consider the accurate fits between sub-components and components. The ease of construction was confirmed by the contractor who has better knowledge about constructability and workmanship. Additionally, the parametric model allowed the structural engineer to conduct structural analysis and ensured the structural performance can meet the standards.

With the help of the parametric design tool, a detailed 3D digital model was finally generated (see Figure 2). The proposed building consisted of 16 frames forming its overall shape and indoor space. Each frame was made up of glue-laminated bamboo (GluBam), polycarbonate hollow sheet, and galvanized steel plate. The wall of the building was made up of GluBam, and the fence was made up of bamboo strip. The material list was also automatically generated by using the parametric design tool. In total, the required material included 72 pieces of large GluBam, 36 pieces of small GluBam, 39 pieces of Φ100 original bamboo, and a small amount of polycarbonate hollow sheets, galvanized steel plates, and accessories. Figure 3 illustrated how each piece of GluBam was fabricated into building components.

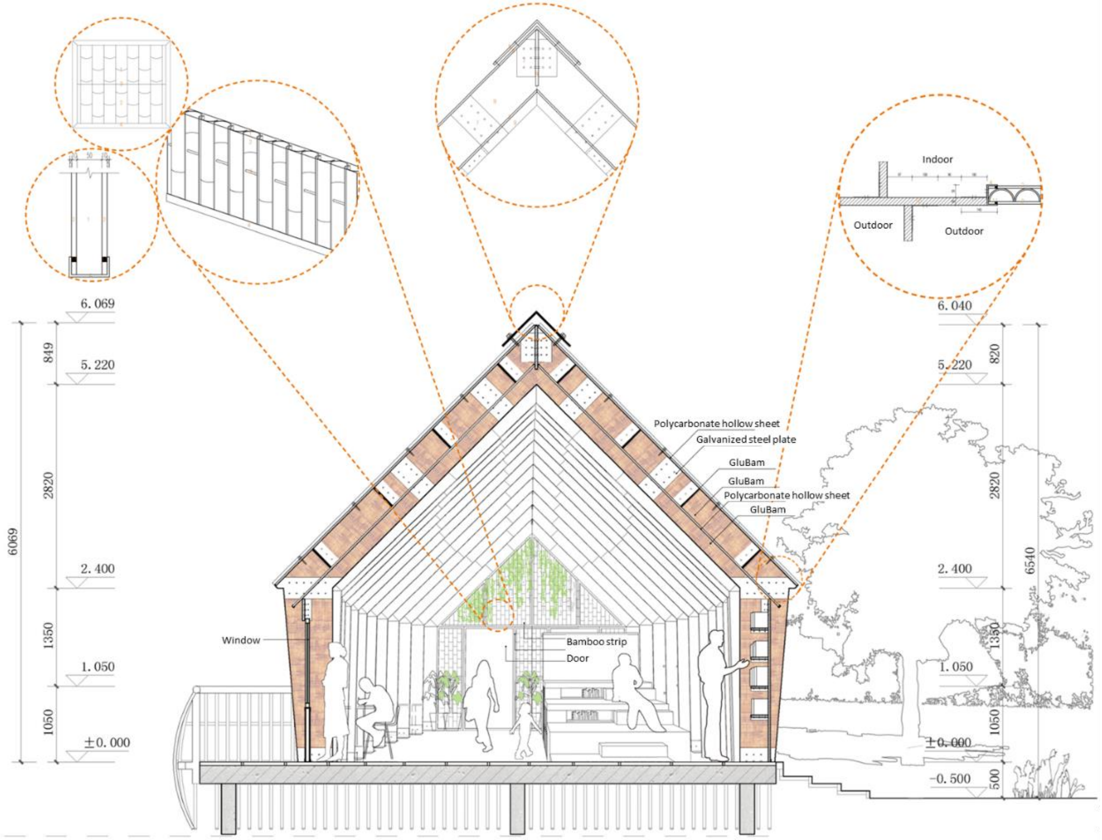

Figure 2. Illustration of the detailed design

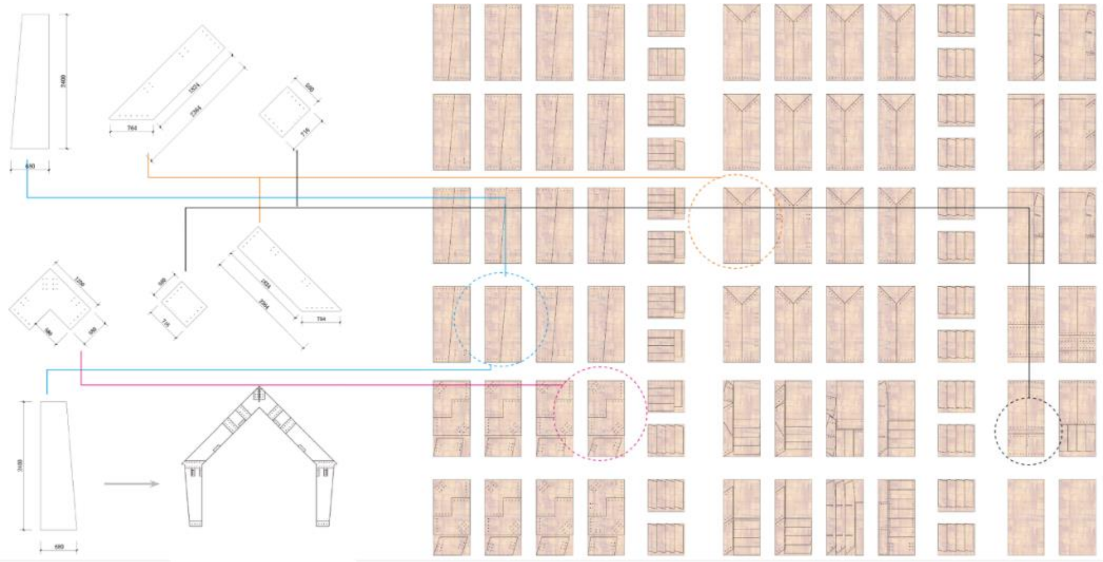

Figure 3. Illustration of building components and sub-components

Project accomplishment

The production and construction drawings were generated from the 3D digital model. The early involvement of contractor in the conceptual and detailed design allowed the contractor to have sufficient understanding of the building to be constructed. The production drawings were provided to the manufacturer to produce the sub-components and accessories for on-site assembly (see Figure 1). The material cost of this project was less than CNY60,000, and the total construction was less than CNY100,000.

After being produced, the sub-components and accessories were transported to the construction site (see Figure 4[a] and Figure 4[b]). Then, on-site assembly work started from connecting individual sub-components by galvanized steel plates and bolts (see Figure 4[c]) to form the building components (see Figure 4[d]). Figure 5(a) shows the construction of the project, which is done by assembling the components piece by piece. The construction work was finished in three weeks, and a glance of the constructed building is presented in Figure 5(b).

(a) On-site material placement (b) Sub-components made of GluBam

(c) Galvanized steel plates and accessories

(d) Connection of sub-components

Figure 4. Production of individual components

(a) Under construction

(b) Completion

Figure 5. Construction of the project

Discussions of DfMA implementation

In this case study project, benefits of DfMA are tangible. First, the design has been checked by all design team members, and all potential conflicts have been addressed in the design phase. Therefore, no change happened during the construction process. Second, DfMA maximized the value-adding work and decrease potential waste in the design phase. Third, DfMA promoted the exploration of different construction methods and materials in order to improve the productivity and quality of construction. All GluBam-made sub-components and components have appropriate size and shape, and their on-site assembly was much simpler and quicker than conventional cast-in-situ construction method. As reflected by the interviewed contractor, the construction of this project might need at least two more weeks without the application of DfMA principles.

The successful implementation of DfMA needs both technological and managerial supports. The use of parametric design tool can help generate the DfMA-oriented design and visualize the results in form of the 3D digital model, but what is more important is the active collaboration among stakeholders so that their knowledge can contribute to the building design. In the case study project introduced in Banks et al. (2018), the DfMA implementation was led by the contractor. However, the case study project reported in this paper adopted a designer-led DfMA implementation. Acknowledging this difference, both case studies suggest that a mindset change in the early design phase should be taken place since DfMA encourages, or even “forces”, the design to incorporate construction. Such requirement makes the conventional sequential project delivery not suitable for DfMA implementation. Methods that can enable a concurrent and integrated project delivery, like the establishment of an interdisciplinary design team, are thus preferred. Such methods can better involve the manufacturing and construction experience into the design. In this way, the determined DfMA principles can be appropriately followed without sacrificing the aesthetics and structural performance of the building.

CONCLUSION

This study investigates the implementation of DfMA in a real prefabricated bamboo building project. It was found that the application of DfMA principles to construction projects requires the designer to fully consider the ease of manufacture and construction in the design phase. Knowledge about manufacture and construction should be provided to the designer as early as possible. Therefore, the establishment of a multi-disciplinary design team might be one of the prerequisites for DfMA implementation. A more effective way to implement DfMA could be the adoption of a more integrated project delivery method, like Engineer–Procure–Construct (EPC), which can largely remove the fragmentation of project stakeholders.

The case study also shows the use of parametric design tool to facilitate the implementation of DfMA, and reveals benefits of DfMA including the increased productivity and quality, reduced production duration, and decreased waste. However, it should be noted that DfMA is complex and incorporates several distinct elements, the data reported in this study may not be enough to illustration the full breadth of DfMA’s benefits. Future work can be conducted to further analyze the implementation of DfMA in other types of construction projects.

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