BIM-enabled Design for Manufacture and Assembly

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Abstract. Design for Manufacture and Assembly (DfMA) has been introduced into the construction industry to enhance production efficiency. DfMA is a design approach and evaluation system for improving manufacturability and assemblability. This paper outlines the past and ongoing Artificial Intelligence (AI) development in manufacturing-oriented DfMA, and provides a literature review of the concept and the use of DfMA in the construction. The applications, challenges and barriers of design optimization through DfMA and BIM-enabled DfMA are summarized. This desk study shows that studies related to construction-oriented DfMA are still in infancy. At present, articles about DfMA are focused on optimizing design and engineering for manufacturability and assemblability, but rarely describe its digital enablement. This study makes up for the lack of literature review in the evaluation of DfMA with concluding a preliminary application framework, and proposes a future-oriented study and new direction for BIM-enabled DfMA.

1. Introduction

The energy consumption and greenhouse gas emissions caused by buildings accounts for about one-third of emissions and may double in 2050 (Abergel et al., 2017), while the United Nations estimates that the urban population in 2050 will increase by 2.5 billion. But today construction delays, cost overruns, and productivity have not significantly changed (Trauner et al., 2017). A strategic approach to increase construction productivity and sustainability is therefore critical. DfMA has been regarded as Circular Economy solutions for sustainable development (Sanchez and Haas, 2018). The United Kingdom (UK), Singapore, and Hong Kong have identified DfMA as the way to transform the construction industry. Leading organisations and institutions are collaborating around DfMA as a philosophy and a methodology whereby products are designed in a way that is as amenable as possible for downstream manufacturing and assembly (O'Rourke, 2013; Balfour Beatty, 2018). The Royal Institute of British Architects (2013), Singapore's Building and Construction Authority (2016), UK's Infrastructure and Project Authority (2018), and Hong Kong's government (2018) are laying out the principles, processes and standards to achieve DfMA, but digital-enabled platforms for DfMA (P-DfMA) a just starting to emerge.

This study is focused on the evaluation of DfMA during design-review (Gao et al., 2019; Yuan et al., 2018) and the use of Building Information Modelling (BIM) policies, principles, rules, tools, technologies and processes (Eastman et al., 2011) to support the development, delivery, management and maintenance of built assets to achieve BIM-enabled DfMA innovation and collaboration (RIBA, 2013; BCA, 2016). Intelligent technologies originated from manufacturing-oriented DfMA are listed and discussed. This paper aims to investigate previous BIM-enabled DfMA studies and their impact on design optimization, and point the way for DfMA intelligent transformation. Firstly, this study investigates current practices and studies of DfMA design optimization. Secondly, the implementation of BIM-enabled DfMA (e.g. as a process, tool and information source). Thirdly, the intelligent technologies in manufacturing-oriented DfMA (e.g. expert systems, case-based reasoning, neural network). Finally, this study proposed future research direction of BIM-enabled DfMA in the construction.

2. Methodology

A two-step method was conducted. The first step is to investigate the state-of-art research of DfMA in construction. Google Scholar, Scopus and Web of Science were searched using the following keywords: "Design for Manufacture and Assembly" OR "Design for Manufacture" OR "Design for Assembly" OR "DfMA" AND "construction industry". The search was limited to peer-reviewed published articles in last 10 years, as most relevant policies and studies of DfMA in construction were produced during this time. Knowing these criteria, the search was performed in December 2019; articles published by then and appearing in the database were considered. Finally, Google Scholar has 739 results; Scopus has 138 results; Web of Science has 344 results. A total of 1221 hits resulted from the initial search. Next, inclusion and exclusion criteria were set. The former includes (1) articles written in English and produced by peer-reviewed articles; (2) articles published in Architectural Engineering and Construction (AEC) – related journals or conferences, and (3) regard DfMA as the key concept in studies. The exclusion criteria include (1) lacking focus on the construction industry and (2) only mention of DfMA rather than in-depth apply or discuss DfMA in studies. Then, conducting snowballing to filter out more related papers which also satisfy the inclusion and exclusion criteria. Snowballing iterated until no new papers were found. Finally, there were 28 articles.

The second step is to retrieve research of intelligent technologies in DfMA. This step is to summarize the common technologies and their application scenario rather than fully list all possibilities, thus the search is limited to peer-reviewed journal articles. Web of Science was used as it can screen out Science Citation Index Expanded journal articles directly. The searching keywords are: ("DfMA" OR "Design for manufacture and assembly" OR "Design for manufacture" OR "design for assembly") AND ("Intelligent Systems" OR "Artificial Intelligence" OR "Expert Systems" OR "Fuzzy Systems" OR "Genetic Algorithms" OR "Knowledge-Based Systems" OR "Neural Networks" OR "Context Aware Applications" OR "Embedded Systems" OR "Human–Machine Interface" OR "Sensing and Multiple Sensor Fusion" OR "Ubiquitous and Physical Computing" OR "Case-based Reasoning"). Finally, Web of Science has 38 results. All these filtered articles are related to DfMA in manufacturing industry. Finally, this study combined the study of BIM-enabled DfMA and Intelligent-enabled DfMA for a prototype framework.

3. Design for Manufacture and Assembly

Originated from manufacturing industry, DfMA combines Design for Manufacture (DfM) and Design for Assembly (DfA) (Bogue, 2012). The main purpose of DfMA is to assist designers in optimizing and increasing productivity by integrating downstream knowledge and information into the design stage. Evaluation of DfMA manufacturability and assembly is critical, to facilitate objectivity in team-based decision making (Leaney, 1996), and simulating it value (Gao et al., 2019).

DfMA is often realised through offsite construction/manufacture. Nevertheless, recently on-site "construction laboratories" have been used to deliver DfMA with local craftspeople, materials, machineries and advanced technologies (Watts, 2018). The need for BIM-enabled DfMA manufacturing and assembly has universal significance, regardless of the difference adoption of construction methods. Bogue (2012), Emmatty and Sarmah (2012) and Safaa et al., (2019) prioritise simple design, minimizing precast component types, using standard and off-the-shelf components, minimizing connector types and quantity, using as similar materials as possible, using as environmental friendly materials as possible, considering modular designs, standardizing handling and logistics, aiming for mistake-proof designs, and considering design for mechanized or automated assembly. Further attention is need to DfMA manufacturability and assemblability evaluation (Gao et al., 2019). Figure 1, shows potential BIM actions for DfMA that require further research and development.

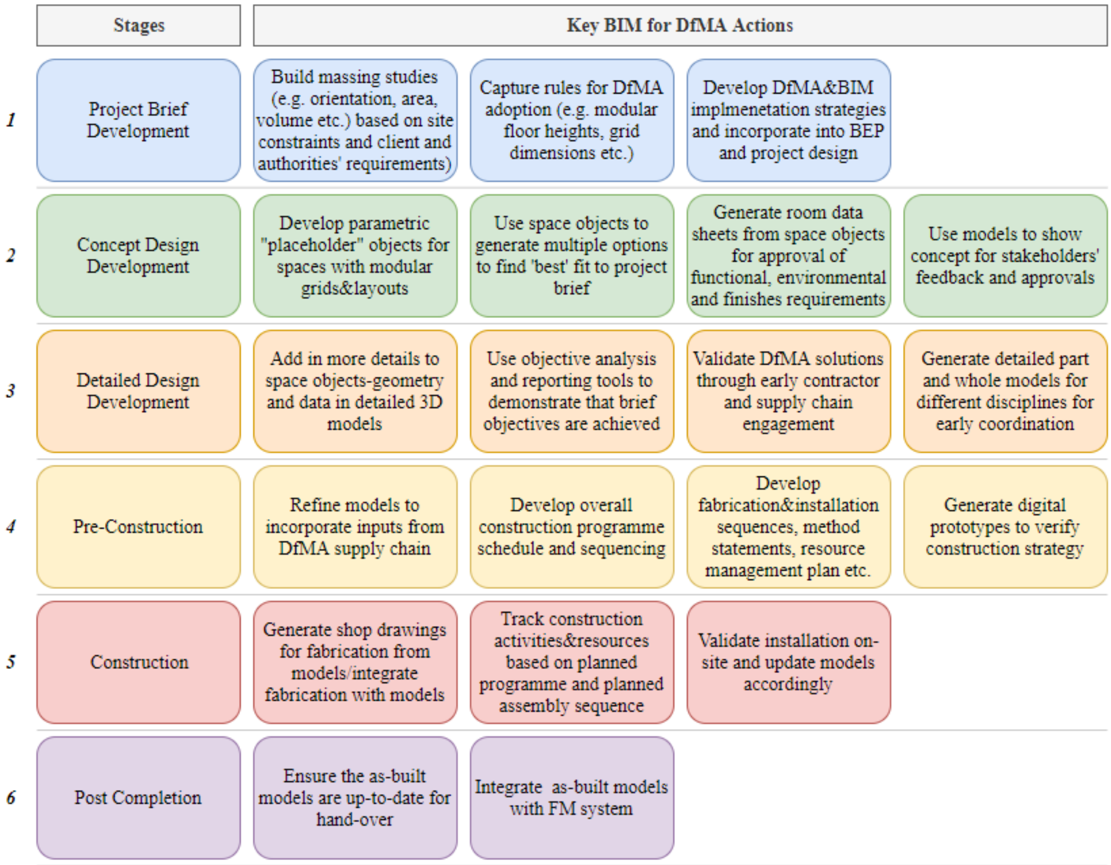

Figure 1: Key BIM actions for the DfMA approach (Derived from BCA, 2016)

4. DfMA Optimization Methods in Construction

Table 1 shows the 11 articles related to DfMA optimization methods and the evaluation of engineering choices or alternatives during design. Significant in this state of the art review is DfMA use for building façades (Montali et al., 2018; Montali et al., 2019; Giuda et al., 2019; Azzi et al., 2011; Başarır and Altun, 2018), weatherproof seals (Orlowski et al., 2018), and modular components (Rausch et al., 2016). Few studies focus on design optimization of the whole built project, although some such as Yuan et al., (2018) have established a process information model for DfMA-oriented prefabricated buildings. While Gerth et al., (2013) combined DfMA, constructability and waste management for the purposes of optimization of housing design.

Table 1: Optimization methods based on DfMA Since 2009

Name	Theory Base	Knowledge Elicitation Methods	Data Analysis Methods	Perspective		Specialize	Reference
				DfM	DfA		
BIM-Based optimizer	DfMA and lean construction	Literature review and questionnaire	Voting-Analytic Hierarchy Process		✓	Building elements and materials	Gbadamosi et al., (2018)

Design for Construction	Constructability, DfMA, and waste management theory	Workshop	Logical argumentation		✓	Housing wall	Gerth et al., (2013)
Knowledge-based engineering	DfMA	Literature review and interview	N/A	✓		Façade	Montali et al., (2018)
Knowledge-rich optimisation	DfMA	Semi-structured interview	N/A	✓		Façade	Montali et al., (2019)
DfMA-based evaluation	DfMA	Questionnaire, interview and observation	Analytic Hierarchy Process	✓	✓	Bridge	Safaa et al., (2019)
BIM-based Approach to Façade Cladding Optimization	Geometry, DfMA, and waste management theory	Project owners	Multi-criteria methodology	✓		Façade	Giuda et al., (2019)
DFMA-oriented prefabricated building information model optimization	DfMA	Expert consultation	N/A	✓	✓	Prefabricated buildings	Yuan et al., (2018)
Optimum assembly planning	DfMA	3D imaging (laser scanning)	Proposed Algorithm	✓	✓	Modular components	Rausch et al., (2016)
Variability-oriented assembly system	Design for assembly and group assembly	Project dataset, interview and site survey	Complete-linkage clustering		✓	Façade	Azzi et al., (2011)
Methodological approach to Design and Development of waterproof seals	DfMA	Expert consultation	N/A	✓	✓	Weatherproof seals	Orlowski et al., (2018)
Redesign procedure to manufacture adaptive façades	DfMA and Theory of Inventive Problem Solving (TRIZ)	Designers and experts	Weighted decision matrix method	✓	✓	Façade	Başarır and Altun, 2018

Optimizing design almost always involves a design trade-off as it needs considering numerous criteria. Multi-criteria methodology was used by the vast majority of these studies. Most are designed to simplify data acquisition. For example, through applying Analytic Hierarchy Process (AHP) or an evolutionary method based on AHP, such as Voting-AHP to apply a criteria weighting. Root cause analysis and cause and effect analysis were also used as the basis of weights (Gerth et al., 2013). Partial limitation of all these methods is the process of subjectively assigning relevance and weighting to assessment criterion. What are more weighting judgements may vary from project to project and may be dependent on different domain knowledge.

Optimization algorithms are also applied to the design process to judge potential alternatives. For example, Rausch et al., (2016) proposed an algorithm to optimally plan, order and arrange components and assess geometric variability and rework. Montali et al., (2019) created a "meta-domain" of analysis to find trade-offs between performance and architectural intent, while allowing for maximum compliance to manufacturing, logistic and design constraints. Manufactured products (such as specific modular components or facades) have been optimized using this method, but rarely whole architectural building solutions (combining strategies to integrate manufacturability and assemblability).

5. BIM-enabled DfMA

BIM has potential to extend the innovative and collaborative use of DfMA at both the object and integrated collaborative environment level (RIBA, 2013; BCA, 2016). Table 2 shows those that have applied BIM and DfMA. Some integrated BIM, DfMA process and strategies for implementation. For example, Machado et al., (2016) establish BIM-based collaborative strategy for DfMA, while Yuan et al., (2018), Kremer (2018) and Samarasinghe et al., (2016) integrate BIM into the design process.

Table 2: BIM-enabled DfMA

Author	Year	BIM application in DfMA
Yuan et al.,	2018	Integrate BIM in design process
Rausch et al.,	2016	Collect geometric data and identify critical points for the assembly from BIM model
Gbadamosi et al.,	2018	Collect geometric data and material information from BIM model
Machado et al.,	2016	Establish BIM-based collaborative strategy
Kremer	2018	Integrate BIM in design process
Lee et al.,	2014	Use BIM tool to process data
Tresidder and White,	2017	Use BIM to develop a checking and review tool
Giuda et al.,	2019	Collect geometrical information from BIM model, and process data using BIM plug-in
Samarasinghe et al.,	2016	Integrate BIM in design process

BIM provides an effective tool for review, checking, and data processing (Lee et al., 2014, Tresidder and White, 2017; Giuda et al., 2019). Open Application Programming Interfaces (APIs) can support BIM software vendors and help third party developers to program advanced software modules for the specialized information process service (Lee et al., 2014). BIM, digital DfMA models, components and connections can be used to streamline the processes of manufacture and assemble. Data-rich models and standardize DfMA elements, such as Prefabricated Prefinished Volumetric Construction (PPVC), Prefabricated Bathroom Unit (PBU), precast components, can support the adoption of a more systematic BIM-enabled DfMA process (BCA, 2016).

The BIM model is an important source of information, which can be analysed and optimised. This could include asset data, geometric data (Rausch et al., 2016; Gbadamosi et al., 2018; Giuda et al., 2019), material information (Gbadamosi et al., 2018), and assembly information (Rausch et al., 2016). These physical BIM properties can be combined with process information and downstream DfMA activities (such as procurement, manufacturing, transportation, installation). These can also be linked to upstream activities (such as briefings, option evaluations, and conceptual design) and increasing consensus among all project stakeholders (BCA, 2016). The structure of BIM and DfMA has been proposed, but under developed.

A BIM-based DfMA process has been established by Yuan et al., (2018). This linear evaluation process has been applied to understand prefabricated building manufacture and assemble. Although most studies are limited in that they focus on either DfM or DfA on industrial manufactured products, rather than architectures. A fully integrated DfMA decision support tool is needed to digitally evaluate across stages of the project lifecycle.

6. Intelligent-enabled DfMA

The application of intelligent technology in the process of DfMA is not a new move. In the past thirty years, with the origin of DfMA theory, related researches have continuously appeared. Commonly used intelligent technologies are shown in Table 3. They are applied for the improvement of process modelling, design estimation and evaluation, assembly/manufacture planning and optimization, recommendations generation, selections comparison, production uncertainty reduction and so on. These issues are also encountered in the process of construction-oriented DfMA. These efforts are for three aspects: (1) design evaluation; (2) design improvement; (3) manufacturing modelling; and (4) assembly planning. However, these intelligent technologies born for manufacturing-oriented DfMA have not been introduced into the construction industry for intelligent upgrading.

Table 3: Intelligent technologies in DfMA

Name	Type	Function	Reference
Experts systems/knowledge-based systems	DfA	Assembly sequence generation	ElMaraghy and Knoll 1991; Li and Chow, 1994; Zha et al., 1999
		Assemblability assessment	Chen et al., 1998; Zha et al., 1999; Mei and Robinson, 2000; Zha et al., 2001b; Shehab and Abdalla, 2006; Sanders et al., 2009
		Satisfying assembly requirements	Mo et al., 1999; Zha et al., 1999
		Flexible assembly planning	Zha et al., 2001a; Zha and Du, 2001; Zha, 2002
		Assembly cost estimation	Shehab and Abdalla, 2006; Sanders et al., 2009
		Assembly technique selection	Shehab and Abdalla, 2006
	DfM	Identifying manufacturing violations	Miller and Colton, 1992
		Modelling DfM process	Bayliss et al., 1995
		Manufacturability assessment	Jung and Billatos, 1993; Yang and Yuan, 1995; Chen et al., 1998; Chan, 2002; Valentinčič et al., 2007
		Facilitating material selection	Shehab and Abdalla, 2001
Case-based reasoning	DfA	Redesigning products with Improved assemblability	Kim, 1997
	DfMA	Machining fixture design in a virtual reality	Gaoliang et al., 2010
Rule-based reasoning	DfMA	Machining fixture design in a virtual reality	Gaoliang et al., 2010
Genetic Algorithms	DfA	Evaluating and selecting parts	Liang and Grady, 1997; Fazio et al., 1999
		Assembly sequence choices	Fazio et al., 1999
	DfMA	Fine-tunes attribute values of the selected design	Changchien and Lin, 2000
Neural network	DfM	Feature recognition	Onwubolu et al., 1999; Marquez et al., 1999
		Material and process parameter selections	Cherian et al., 2000

	DfA	Assembly time estimation	Namouz and Summers, 2013; Owensby and Summers, 2014
Fuzzy logic	DfA	Fuzzy assessment	Zha et al., 1999; Zha and Du, 2001; Zha, 2002
	DfMA	Generate accurate cost estimates	Shehab and Abdalla, 2001
Multi-agent system	DfA	Assembly planning	Zha, 2002

7. Discussion

This literature was mainly concentrated on the level of engineering efficiency of manufacturability and assemblability. Both BIM and intelligent technologies show the ability to facilitate the improvement of evaluation and decision-making for choices or alternatives. The application of BIM includes: (1) to enable the process of DfMA; (2) as a tool for DfMA; (3) as an information source / model for DfMA. Together with BIM, construction-oriented DfMA can adopt intelligent technologies which has been introduced into manufacture-oriented DfMA. A framework of BIM-enabled DfMA with intelligent technology was summarized from the review. As shown in Figure 2, BIM-enabled intelligent toolkit and BIM sources can support the DfMA for a multi-criteria methodology. A more integrated intelligent decision system can be built on this basis to help achieve better manufacturability and assemblability.

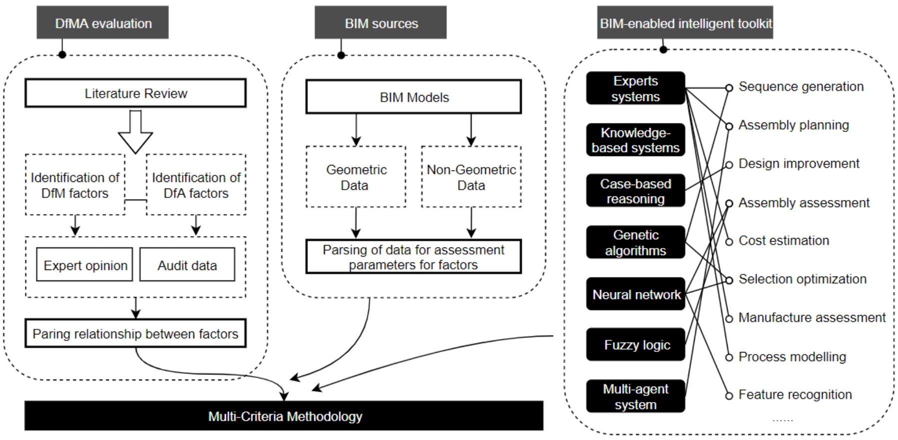

Figure 2: Prototype of BIM-enabled DfMA

However, DfMA intelligent technologies in the manufacturing industry have gone through more than twenty years of development, whereas the corresponding research in construction industry is still in its blank. These mature technologies have not been applied to the design of the construction industry. Due to the characteristic of construction, the process of digital enablement for DfMA cannot be directly transforming from the knowledge of the manufacturing industry. The construction industry does not simply rely on large-scale factory production to complete the entire production process as construction always needs on-site completion. With the development of construction industrialization, it provides an opportunity for the introduction of intelligent technologies. Especially in some building types, such as hospital, factory and house, the application prospect of these intelligent technologies will be more extensive. However, the limitation is that most of these studies in manufacturing were carried out about 20 years ago. The construction industry can get some inspiration for transformation from these mature applications, but still needs to be combined with the technological context of today's era. Further research is needed to bridge these applications to establish a new approach to BIM-enabled design optimization. Researchers need to go beyond the perspective of building components to explore the optimization of the entire building process. At the same time, different prefabrication ratios will result in different workloads at the factory and on-site, and all these factors need to be considered during the optimization method generation.

8. Conclusion and Future Work

This study reviewed previous studies DfMA design optimization studies, and explored their combination with BIM and intelligent technologies. This literature was mainly concentrated on the level of engineering efficiency of manufacturability and assemblability. Uses of BIM-based DfMA included the use of BIM: (1) to enable the process of DfMA; (2) as a tool for DfMA; (3) as an information source / model for DfMA. In addition, construction-oriented DfMA can adopt intelligent technologies which has been introduced into manufacture-oriented DfMA to tackle similar issues. Further research is needed to bridge these applications to establish a new approach to BIM-enabled design optimization. This could include:

• The integrated consideration of manufacturability and assemblability, rather than linear process evaluation and current multi-objective optimization methods.

• Advanced data and pairing to allow expert judgment. The use of historical data and machine learning algorithms may be supplemented by expert opinions to form a hybrid approach.

• Optimization for whole building architectures (e.g. complex healthcare, airport, transportation hub and so on), rather than single building components.

• Comparing different BIM-based DfMA strategies at different prefabrication levels (e.g. the higher the prefabrication, the higher the demand for manufacturing, and less on-site assembly). How to establish a corresponding design optimization method based on the changes in the proportions of these two aspects should be considered.

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