19. Building information modeling-enabled platform approach to design for manufacture and assembly

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1. INTRODUCTION

The architecture, engineering and construction (AEC) industry is increasingly dealing with the fragmentation of the sector (Alashwal and Fong, 2015; Dulaimi et al., 2002; Fulford and Standing, 2014; Mohd Nawi et al., 2014). Conventional design and construction methods are facing growing challenges from emerging technologies, such as building information modelling (BIM) and design for manufacture and assembly (DfMA). BIM-enabled DfMA is expected to introduce downstream knowledge and information into the upstream design process, and help realize the 'off-site revolution' (Tan et al., 2020b). In the last decade, construction industry strategies of many countries widely adopted DfMA. Policy makers and key industry leaders in the United Kingdom, Singapore and Hong Kong have identified DfMA as the way to transform the construction industry. Leading organizations 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 (Beatty, 2018; Gao et al., 2020; O'Rourke, 2013). The Royal Institute of British Architects (RIBA), Singapore's Building and Construction Authority (BCA), the UK's Infrastructure and Project Authority (IPA), and Hong Kong's government are defining principles, processes and standards to achieve DfMA, but a digital-enabled Platform Approach to DfMA (P-DfMA) is early in its infancy.

In 2018, the UK government's National Infrastructure and Construction Pipeline initiated a platform approach to design for manufacture and assembly (Infrastructure and Projects Authority, 2018a), to kickstart a transformation from the conventional 'pipeline' to a platform (Van Alstyne et al., 2016). Related UK policies suggest the use of uniform methods for design and construction in different government departments by using standardized and interoperable components from a wide base of suppliers across a range of different building types, which aims to drive a new market for manufacturing in construction and thereby take advantage of economies of scope and efficiencies of scale (Infrastructure and Projects Authority, 2018a). The emergence of platformization was first seen in other fields. Platform-based companies, such as Google, Apple, and Alibaba, have attracted the attention of many researchers for the resulting winner-takes-all outcomes. This vision is also introduced into the plan for AEC development and continuous innovation (Bonev et al., 2015; Jansson et al., 2014; Lennartsson and Elgh, 2018; Wood, 2018). The research community needs to expand its focus from a single building type, commonly house building (Lennartsson and Elgh, 2018; Popovic et al., 2019; Thajudeen et al., 2018; Thuesen and Hvam, 2011; Wikberg et al., 2014; Wörösch et al., 2013), or a single construction method, mostly industrialized construction (Bonev et al., 2015; Holmquist, 2014; Jansson and Viklund, 2015; Maxwell, 2016; Thajudeen et al., 2018; Wikberg et al., 2014), to consider the wider platform involving integrated production of various building types and construction methods, i.e. DfMA is for an overall consideration of a series of different projects rather than only project-based one-off design.

BIM is a digital representation of a constructed facility (Eastman et al., 2011) and offers an important line of 'integration' (Chen et al., 2015), and a multi-disciplinary collaboration platform (Singh et al., 2011), which is likewise critical for the delivery of P-DfMA. BIM provides new opportunities to further harness the proliferation in various building types when adopting P-DfMA. In order to realize the vision of P-DfMA, previous studies about DfMA and P-DfMA are explored alongside BIM in this chapter. The concept of product platform from the manufacturing industry is also introduced. The aim of this chapter is twofold: to define the concepts of DfMA, BIM and platformization and to propose a process for developing a BIM-enabled DfMA platform and conclude with implications for practice.

2. METHODOLOGY

A two-step method has been adopted for this exploratory study. First, DfMA and BIM were investigated to understand their potential for integration to enhance collaboration. A systematic review was conducted and presented at the EG-ICE International Workshop on Intelligent Computing in Engineering (Tan et al., 2020b). An initial BIM-enabled DfMA framework is proposed. A single case where the first author was directly involved as a Design Manager is also presented. This action research study involved working directly with the design team to investigate design change management and the impact on the construction process. The project was selected as it was the biggest prefabricated wood structure building in China that implemented DfMA.

Second, platform-related concepts were investigated, including platform strategy, product platform and P-DfMA to explore how to leverage DfMA by platform. A BIM-enabled P-DfMA framework was proposed that directly addresses the research gap and practical needs. The case study used is the SEISMIC Primary Schools Configurator developed by Bryden Wood, which was one of the UK's first P-DfMA developments and has influenced wider P-DfMA developments in the construction industry. We conducted a preliminary analysis of this project to analyse the current attempts of the product platform concept in the construction industry and have been directly involved in making recommendations and providing guidance for both SEISMIC II and national policy development.

3. BIM-ENABLED DESIGN FOR MANUFACTURE AND ASSEMBLY

3.1 Design for Manufacture and Assembly

DfMA originated during the Second World War when Ford and Chrysler applied it as a principle in their weapon production processes. At first, it was used in the manufacturing industry. Design for manufacture (DfM) and design for assembly (DfA) emerged in the late 1960s and early 1970s, reflected in UK standards published in 1975 on the management of design for economic production. The academic exploration of DfMA also began in the 1970s with the practice and research of Boothroyd and Dewhurst. Since then, there has been much development of DfMA within the manufacturing industry.

According to Boothroyd (2005), DfMA provides a methodology for evaluating and improving product design by considering the downstream processes of manufacturing and assembly. It thereby signifies a shift from traditional, sequential design process to a non-linear methodology. The implementation of DfA and DfM has the potential to bring considerable benefits, including reducing assembly and manufacturing costs, improving quality, and shortening production time by simplifying products. But these are only considerations of production efficiency. Due to the requirements of sustainability, some scholars have begun to consider the processes of disassembly and recycling during the design phase.

Researchers are beginning to focus on the design of the environment, recyclability, lifecycle, etc. These studies are sometimes referred to as design for excellence (DfX) (Kuo et al., 2001). DfX is a related methodology, where the ‘X’ refers to excellence in aspects including testability, compliance, reliability, manufacturability, inspection (DfI), variability (DfV), and cost (DfC). DfX in general aims to provide a standard philosophy, methodologies, and tools to optimize a design (Huang, 2012; Gatenby and Foo, 1990; Kuo et al., 2001). For example, DfX techniques can improve quality, efficiency, productivity and design flexibility, and decrease lifecycle costs using concurrent design concepts (Maskell, 1991). DfX research emphasizes the consideration of all design goals and related constraints in the early design stage (Kuo et al., 2001). Huang (2012) describes two streams of ‘X’, one with emphasis on a particular business process and the other on a performance metric. DfA falls into the former since it focuses on the assembly process while using multiple performance measures, such as inspectability, compatibility, recyclability, serviceability, etc. Design for modularity, on the other hand, is an example of the latter since it looks into modularity across several business processes from manufacturing to assembly, installation, distribution, and operation. DfMA falls into the business process stream, while both the manufacturing and the assembly processes serve as focal issues. Since the late 1990s, hundreds of papers have been published on the application of DfX in manufacturing. However, this phenomenon has not taken off in the construction industry. This makes it difficult to find all the information needed to apply DfX in the construction industry.

3.2 DfMA Optimization Methods in Construction

Since its adoption in manufacturing, DfMA has helped many companies increase their profits through optimized design (Gatenby and Foo, 1990; Kuo et al., 2001). From a systematic literature review, Table 19.1 lists 11 influential studies 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 parts of construction projects, e.g. building façades (Azzi et al., 2011; Başarır and Altun, 2018; Di Giuda et al., 2019; Montali et al., 2018; Montali et al., 2019), weatherproof seals (Orlowski et al., 2018), and modular components (Rausch et al., 2017). 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. Whereas Gerth et al. (2013) combined DfMA, constructability and waste management for the purposes of optimization of housing design.

Table 19.1 *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. (2019)
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 optimization	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	Di 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. (2017)
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)

Source: Tan et al. (2020b).

Optimizing design almost always involves a design trade-off as it needs to consider numerous criteria. Multi-criteria methodology is used to simplify data acquisition.[1] Optimization algorithms are frequently used to judge potential alternatives. For example, Rausch et al. (2017) 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 façades, have been optimized using this method, but rarely whole architectural building solutions combining strategies to integrate manufacture and assembly.

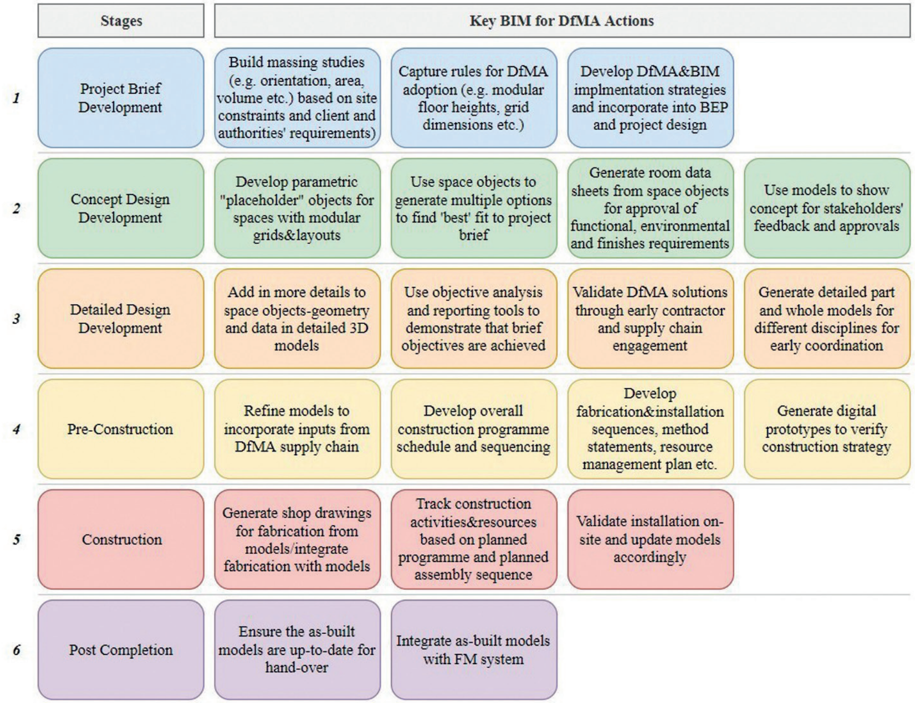
3.3 BIM-Enabled DfMA

BIM is a digital representation of building facilities (Eastman et al., 2011), and a rich multi-disciplinary data repository, including geometry through three-dimensional (3D) models, semantics, which is component specifications and attributes, and topological information regarding component dependencies (Fouchal et al., 2014). These capabilities provide attractive opportunities for integrating the fragmented AEC industry. The need for BIM-enabled DfMA manufacturing and assembly has universal significance, regardless of the difference in adoption of construction methods. Figure 19.1 shows potential BIM application areas for DfMA that require further research and development. BIM has the potential to extend the innovative and collaborative use of DfMA at both the object and integrated collaborative environment level (BCA, 2016; Sinclair, 2013; Development Bureau, Government of Hong Kong, 2018).

Table 19.2 shows key studies that document the simultaneous application of BIM and DfMA. Some studies illustrate integrated BIM, DfMA process and strategies for implementation. For example, Machado et al. (2016) established BIM-based collaborative strategy for DfMA, while Yuan et al. (2018), Kremer (2018) and Samarasinghe et al. (2016) integrated BIM into the design process.

BIM-based DfMA uses a BIM process, tool and information source (the DfMA model) (Tan et al., 2020b) to review, check and process data (Di Giuda et al., 2019; Lee et al., 2014; Tresidder and White, 2018). BIM, digital DfMA models, components and connections can be used to streamline the processes of manufacturing and assembly. Data-rich models and standardized 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 optimized. This could include asset data, geometric data (Di Giuda et al., 2019; Gbadamosi et al., 2019; Rausch et al., 2017), material information (Gbadamosi et al., 2019), and assembly information (Rausch et al., 2017). These physical BIM properties can be combined with process information and downstream DfMA activities (such as procurement, manufacturing, transportation, installation). These properties 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 is underdeveloped. A BIM-based DfMA process is established by Yuan et al. (2018) as a linear evaluation process and applied to understand prefabricated building manufacture and assembly, but few studies take a platform approach that integrates both DfM and DfA. A new construction-oriented BIM-enabled DfMA framework has been established to prototype how



Source: BCA (2016).

Figure 19.1 *Key BIM actions for the DfMA approach*

Table 19.2 BIM-enabled DfMA

Authors	Year	BIM application in DfMA
Yuan et al. (2018)	2018	Integrating BIM into the design process
Rausch et al. (2017)	2016	Collecting geometric data and identify critical points for the assembly from BIM model
Gbadamosi et al. (2019)	2018	Collecting geometric data and material information from BIM model
Machado et al. (2016)	2016	Establishing BIM-based collaborative strategy
Kremer (2018)	2018	Integrating BIM in design process
Lee et al. (2014)	2014	Using BIM tool to process data
Tresidder and White (2018)	2018	Using BIM to develop a checking and review tool
Di Giuda et al. (2019)	2019	Collecting geometrical information from BIM model, and process data using BIM plugin
Samarasinghe et al. (2016)	2016	Integrating BIM in design process

Source: Adapted from Tan et al. (2020b).

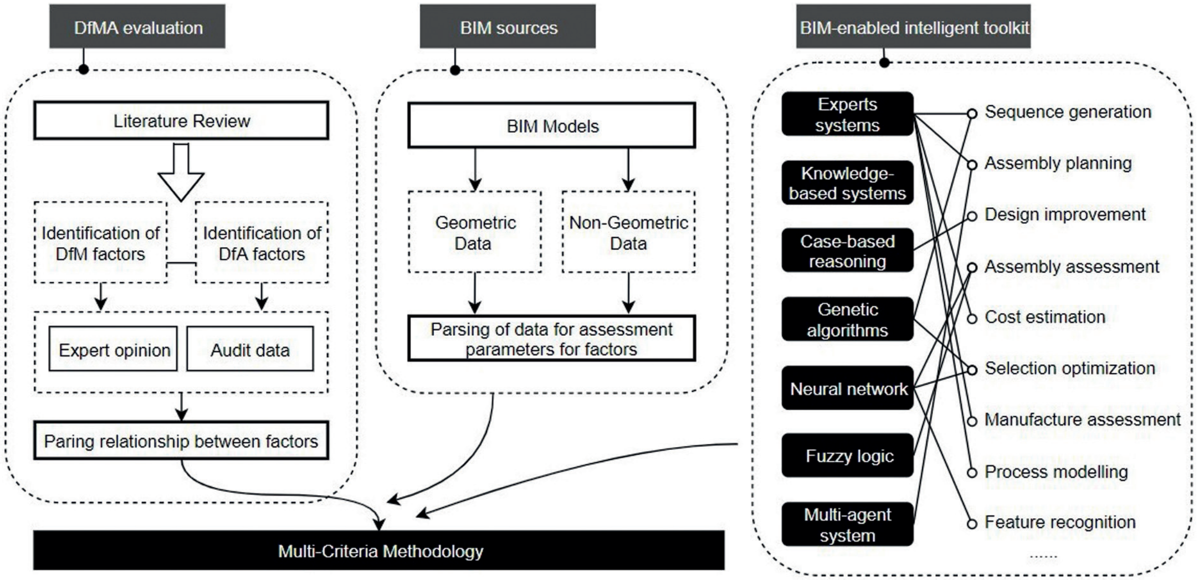
intelligent technologies, previously introduced into manufacturing, may be adopted (Tan et al., 2020b). Figure 19.2 hypothesizes how a BIM-enabled intelligent toolkit, BIM sources, and DfMA evaluation approach could inform a multi-criteria methodology. A more integrated intelligent decision system can be built on this basis to help achieve better manufacturability and assembly.

Artificial Intelligence (AI), such as knowledge-based systems, case-based reasoning, neural network, and genetic algorithms, is not a new field in manufacturing-oriented DfMA, which already has about 30 years' history. These efforts are applied to four aspects: (1) design evaluation; (2) design improvement; (3) manufacturing modelling; and (4) assembly planning (Tan et al., 2020b). However, these mature technologies have not been fully applied to the design in the construction industry. Construction types, such as those with prominent engineering properties and scale such as hospitals, factories and houses could benefit significantly from wider adoption.

Further research is needed to bridge factory- and site-based applications to establish a new platform approach to BIM-enabled intelligent design optimization. Firstly, the integrated consideration of manufacturability and assemblability, rather than linear process evaluation and current multi-objective optimization methods. Secondly, advanced data and pairing to allow expert judgement. The use of historical data and machine learning algorithms may be supplemented by expert opinions to form a hybrid approach. Thirdly, optimization for whole building architectures, e.g. complex healthcare, airport, transportation hub and so on, rather than single building components. Finally, comparing different BIM-based DfMA strategies at different prefabrication levels, e.g. the higher the prefabrication, the higher the demand for manufacturing, and less onsite assembly.

3.4 Case Study Showing the Application of BIM-Enabled DfMA

The investigated ongoing project is a museum for the Tujia minority. It is the largest building with a prefabricated wood structure in China. Raw timber was imported from Canada to Wuhan, China within about 45 days. After the wood products were processed to prefabricated components in the Wuhan factory, they were transported to Enshi, a mountainous construction site about 600 km away from Wuhan. NURBS modelling software and virtual programming plugin interfaces were used in the split design of the wooden structure, as the robotic arm can



Source: Tan et al. (2020b).

Figure 19.2 Prototype of BIM-enabled intelligent DfMA directly read the 3D models from Rhino, which greatly improves the productivity of manufacturing (see Figure 19.3). By avoiding the conversion from 3D models to 2D drawings, this machine-level collaboration reduced the occurrence of human errors and improved the efficiency of integrated design. The integration of 3D models and 2D drawings fits the philosophy of BIM. In the onsite assembly, the project manager from the split design team directly read the 3D model and related technical drawings to guide workers, which reduced the occurrence of errors (see Figure 19.4).

Notably, the vision of BIM integration has not been maximized. This building is not a full-level prefabricated building. Part of the building, especially the foundation, is made of cast-in-place concrete, which is constructed by another contractor through conventional construction methods. The implementation of BIM has not been implemented in the entire project supply chain. Although the manufacturing process of building construction has greatly improved efficiency through mechanical assistance, the construction of the entire project still poses a great challenge to the cooperation of multi-stakeholders. This project embodies the potential of BIM-enabled DfMA to improve engineering efficiency on a technical level, and also shows that the promotion of BIM at the process level cannot be ignored.

Source: Image by Woodtech.ai.

Figure 19.3a Offsite manufacturing: Raw materials transported from Canada

4.1 Platform Strategy

Platformization is gradually being recognized as an emerging concept for innovating business models and design methods in the construction industry (Bonev et al., 2015; Jansson et al., 2014; Johnsson, 2013; Thuesen and Hvam, 2011; Yashiro, 2014). Platform-based companies, such as Google, Apple and Alibaba, have attracted the attention of many researchers for the resulting winner-takes-all outcomes. Two main perspectives provide the definition of a platform. From the economic perspective, a platform is a type of market (Rochet and Tirole, 2003) or business model (Van Alstyne and Parker, 2017). From the engineering design perspective, a platform is a modular technological architecture (Baldwin and Woodard, 2009).

Source: Image by Woodtech.ai.

Figure 19.3b Offsite manufacturing: Processing by robotic arm

Source: Image by Woodtech.ai.

Figure 19.4a Onsite assembly: Connection steel components

Platforms can be seen as sharing some common features: (1) a set of low variety core assets; (2) a complementary set of peripheral components that exhibit high variety; (3) a stable interface that acts as a bridge between the stable core and variable peripherals, permitting innovation in both core and peripherals. These three similarities reflect three logics in platforms, namely connecting, sharing and integrating (Eloranta and Turunen, 2016). The platform, as a boundary object, attempts to integrate multiple functions and activities, and to standardize workflows while still preparing for contingencies and local contexts at the same time (Styhre and Gluch, 2010). In other words, platformization aims to replace the existing internal processes with new external interactions for value creation (Van Alstyne et al., 2016).

Source: Image by Woodtech.ai.

Figure 19.4b *Onsite assembly: Assembled wooden structure*

4.2 Product Platform

Product platforms have been applied to construction since the 1960s (Johnsson, 2013; Thajudeen et al., 2018). Like DfMA, a product platform is introduced from the manufacturing industry, and is the collection of modules or parts that are common to a number of products (Meyer and Lehnerd, 1997). The core of product platform development is to obtain the biggest set of products through the most standardized set of basic components and production processes (Stadzisz and Henrioud, 1995). As shown in Figure 19.5, through a product platform, companies can develop competitiveness and innovation in their differentiated products (Wheelwright and Clark, 1992).

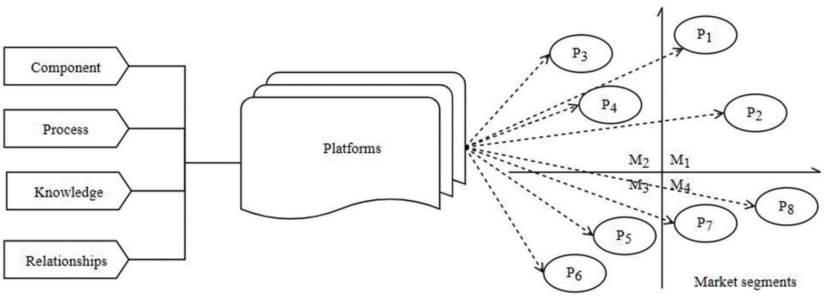


Figure 19.5 *Product platform*

Two main approaches to developing a product platform have been reported (Simpson, 2004), named top-down (proactive platform) and bottom-up (reactive redesign). The former develops a family of products based on a product platform and its derivatives, while the latter redesigns and/or consolidates a group of distinct products into a family to standardize components (Simpson, 2004; Simpson et al., 2006). In the AEC industry, the bottom-up approach requires companies to have a series of standard component libraries from their different building types, and requires they to have the ability and market to carry out prefabricated building design in multiple building categories, which is challenging for many companies. The top-down approach allows companies to develop a product platform for their future market based on their market strategies and abilities. These two types are suitable for AEC companies at different stages of development. Further platform development of BIM-enabled P-DfMA can be built on these bases.

4.3 Advancing Digitally Enabled Platform Approach

Several studies have applied the concept of platform and product platform. For example, Oprach et al. (2019) proposed an artificial intelligence-enabled platform for the construction industry to process heterogeneous data. Styhre and Gluch (2010) highlighted the instrumental ability of platforms for managing construction knowledge. Thuesen and Hvam (2011) studied innovation in a German housing platform. Maxwell (2016) discussed the platform concept in Swedish industrialized construction. Yashiro (2014) proposed a conceptual framework for platform-oriented industrialized buildings in Japan. Hall et al. (2020) highlighted the importance of platforms for enabling vertical integration in Silicon Valley construction firms. Previous studies show that some construction companies have already been using the concept of platform for innovation and benefits of scaling.

The focus of previous research has not yet formed a sufficiently large platform, which means research studies either focus on a single building type or a single construction type. The former one is mainly about house building (Lennartsson and Elgh, 2018; Popovic et al., 2019; Thajudeen et al., 2018; Thuesen and Hvam, 2011; Wikberg et al., 2014; Wörösch et al., 2013), and the latter is mainly industrialized construction (Bonev et al., 2015; Holmquist, 2014; Jansson and Viklund, 2015; Maxwell, 2016; Thajudeen et al., 2018; Wikberg et al., 2014). It can be seen that these types of buildings tend to have relatively small clear height and clear span. The level of repeatability is relatively more standard and level of complexity is relatively low. Building types with these characteristics are easier to implement platform-based production strategies. However, to fully stimulate the power of a platform, research and practice should go beyond the original single scope to various building types and construction types. A platform needs to involve the bilateral consideration for both industrialized and non-industrialized construction across different building types, e.g. to hospitals, schools, prisons, and museums. A platform far exceeds the standardization of components, although they share many development and production resources (Stubbe, 2003).

4.4 Platform Approach to Design for Manufacture and Assembly

P-DfMA is a specific policy initiative to achieve product platformization. To improve the performance of government-led building projects, P-DfMA was proposed by the UK government as a ‘new approach’ to building across its many government departments. This emerging concept integrates platform and DfMA. The government hopes to encourage the establishment of new markets for the manufacturing of construction industry by taking a consistent approach and using standardized and interoperable components, taking advantage of economic and scale benefits. The official definition of P-DfMA from the UK government is:

> A platform approach to DfMA (P-DfMA) means that will we use a set of digitally designed components across multiple types of built asset and apply those components wherever possible, thereby minimising the need to design bespoke components for different types of asset. (Infrastructure and Projects Authority, 2018b)

Unlike many practices that have already applied the platform strategy to house building, P-DfMA hopes to include various types of buildings beyond the scope of a single sector by using a set of standardized and interoperable components. In addition, the definition highlights the digitally designed components rather than solely physical components. This new concept strongly embraces the process of architecture digitalization and attempts to use this process as a transformation opportunity for the construction network to achieve value co-creation among virtual design and manufacturing processes. Generally, P-DfMA is a digitally enabled approach. From the government definition and proposal, three principles underlie the definition of P-DfMA: (1) design for manufacture; (2) use a platform approach; and (3) open for manufacture, use and procurement. These principles emphasize different aspects of P-DfMA. Design for manufacture focuses on the efficient manufacturing process of digitally designed components. Using a platform approach is based on the preference of application scenario across different types of built asset and sectors. The principle of openness aims to encourage the value co-creation of all stakeholders in the network value chain. The initiative of P-DfMA proposes a great vision for the construction industry, tries to encourage its expansion through government projects, and calls for more practical evidence from the industry. However, the research on related application frameworks and auxiliary tools is still at a very early stage.

5. BIM-ENABLED P-DFMA

5.1 Concept of BIM-Enabled P-DfMA

It is well known that BIM supports a platform approach (Farr et al., 2014; Gu et al., 2008; Ma and Sacks, 2016; Singh et al., 2011). However, most are project-level platforms and few span sectors and multiple projects. This is perhaps because of the barriers to the development of an inter-organizational approach to a platform strategy or the technological barriers in developing a digital component library platform. But great strides are being made towards unlocking these barriers today. BIM-enabled P-DfMA is establishing components and BIM libraries across multiple types of built asset. The basic idea of BIM-enabled P-DfMA is to divide traditional architectural design into two tasks: BIM-enabled product platform design and derivative architectural design.

5.2 Case Study Showing the Application of BIM-Enabled P-DfMA

BIM supports a platform approach which makes it easier for clients to procure offsite, for the supply chain to manufacture components, and for offsite specialists to increase productivity as a result of higher volume. However, most are project-level platforms and few span sectors and multiple projects. This is perhaps because of the barriers to the development of an inter-organizational platform strategy, or the technological barriers in developing a digital component library platform. Although some are attempting to use BIM-enabled P-DfMA to establish components and BIM libraries across multiple types of built asset. The basic idea of

BIM-enabled P-DfMA is to divide traditional architectural design into two tasks: BIM-enabled product platform design and derivative architectural design. SEISMIC I is an example of the use of BIM-enabled P-DfMA to solve a specific problem for primary schools in the UK.

Working with the Department for Education, a consortium of partners including Bryden Wood, Blacc, the Manufacturing Technology Centre (MTC), and two of the UK's leading offsite specialists, Elliott and The McAvoy Group developed a BIM-enabled P-DfMA. They developed common room standards, which in turn enabled a reduced and simplified process of component selection and manufacture.

The SEISMIC modules are designed on a standard grid (3,600 mm × 18,000 mm) with a common connecting solution. The was determined largely by transportation limitations which allowed small rooms to be completely fitted out under factory conditions. It achieved BIM-enabled P-DfMA through two approaches described below:

- **The Seismic School Configurator** – a web-based digital application that enables spatial configuration according to specific school requirements and needs (Figure 19.6). DfMA principles are incorporated into a game-style configurator, which made it more usable and accessible to all types of users from children and school leaders, to planners and architects. It is said to enable the involvement of a wider facilitated group of stakeholders, to accelerate the initial design phase and optimize the offsite solution.
- **An open-source approach** – the SEISMIC Configurator has been provided open-source to help build a development community. Because it is compliant with Department for Education (DfE) planning guidance it can be used by other architects, contractors and manufacturers to support compliance. A modular frame was also provided to the market and used by DfE's framework partners. The next phase of the SEISMIC P-DfMA approach was to test the frame solution and scale the steel fabrication, then develop more standard components (both in education and further afield) and stimulate wider supply chain partnerships to aggregate demand and reduce cost.

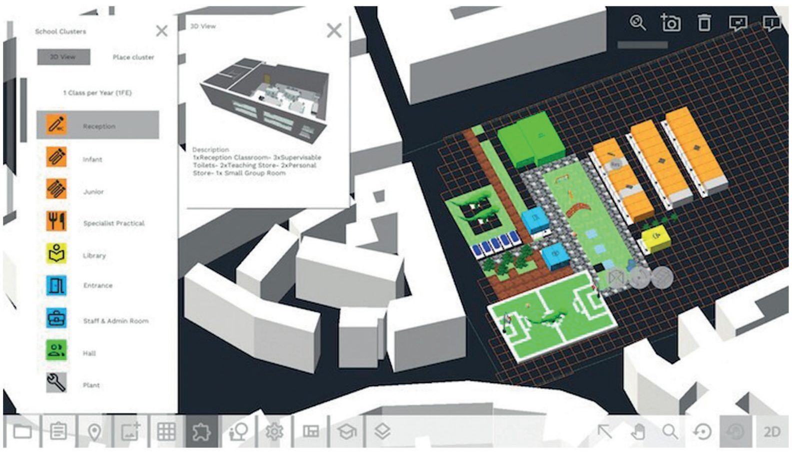


Figure 19.6 SEISMIC Primary Schools Configurator developed by Bryden Wood

5.3 Development Process for BIM-Enabled P-DfMA

Standardization and mass production are key to efficient manufacturing, e.g. fewer components, reduced labour costs and a focus on material and quality. Generally, platform design and development go through three main steps (Robertson and Ulrich, 1998): (1) products' requirements are identified through marketing, customer surveys, or technical design standards; (2) commonality between the functions and components of all products are identified; and (3) differentiation plans are generated to achieve design variety with minimal level of disruption to the common platforms. As shown in Figure 19.7, a five-step process is proposed to adapt the product platform to the construction industry and to develop segments.

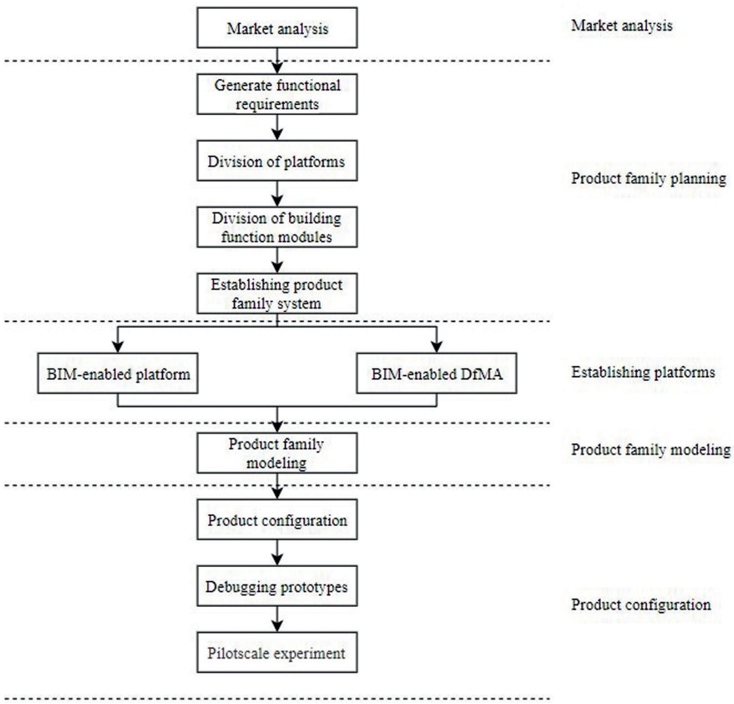


Figure 19.7 Process of BIM-enabled platform

The SEISMIC case study demonstrates this process well. They developed a 'product family' for different types of buildings, such as residential and education. They are investigating a whole school solution (including walls and roofs) as part of the 100 new and replacement primary schools that are needed every year in the UK at a cost of £5 billion. This is part of the market, but the consortium is also considering other associated market demands (with other common functional modules and building components). This approach to establishing an architectural product family system has been applied previously, but not at such a large scale

(Jiao and Tseng, 1999). The SEISMIC consortium continues to develop the platform. This includes:

- Development of a platform with external wall, floor and roof elements and supply chain engagement to develop existing products that can integrate with the platform solution to create reconfigurable components reducing waste, cost and carbon dioxide emissions and increasing speed of delivery.
- Components to maximize the passive performance facilitating the design of energy positive buildings with embedded data driven metrics providing better-performing buildings, built more quickly at lower cost.
- Optimization of connector and frame design through early engagement with the specialist supply chain and creating a network of specialist fabricators. Innovate for buildings over four storeys and vehicle platforms.
- Environmental prototyping, internal and external wall solutions, integrated MEP design, façade, ceiling and roof solutions to develop an active componentized solution and selection of materials (high performance and flexible composite solutions and new fabrication, off-grid/energy carbon reduction).
- Design for manufacture and assembly software platform, process flow and decision support tool. Including an automated/parametric concept and productionization of the manufacturing process to include factory floor, quality systems, logistics, and skills development.

The long-term advantage is that school estates can be developed incrementally over time to meet changes in demand and create efficient layouts. Common structural solutions with fewer welds and fewer connections and a kit-of-parts reduce the need for redesign. Standardized frame dimensions, simplified design and stronger compliance with DfE requirements are some of the stated benefits. Also, work is underway to measure the impact of less steel, less weight, faster assembly and therefore reduced cost.

6. PROSPECTS AND CHALLENGES OF P-DFMA

DfMA has been widely adopted by advanced construction companies around the world as a core strategy to improve the efficiency and effectiveness of project delivery. But there is still some way to go in both adoption and evidence capture. Some companies, for example, are adopting modularization, prototyping, design production checks and offsite manufacture, but fewer are adopting component-led design and pre-assembly. BIM has potential to extend the innovative and collaborative use of DfMA at both the object and integrated collaborative environment level (BCA, 2016; Sinclair, 2013). The need for BIM-enabled DfMA manufacturing and assembly has universal significance, regardless of the different adoption of construction methods (Tan et al., 2020b). Initial evidence shows that BIM-enabled P-DfMA will increase productivity in construction, but there are significant challenges in scaling the capabilities of knowledge sharing, business model innovation, flexible process and economy of scale. With the increasing political interest in the UK, P-DfMA has attracted research focus over the last two years. This trend is also seen in the USA, Hong Kong, Singapore, Australia and China.

The transformation from project-level DfMA to cross project-level P-DfMA is challenging. Styhre and Gluch (2010) suggest platform implementation is difficult due to the institutional avoidance of standardized solutions and off-the-shelf design of buildings. Some industry practitioners are responding to calls by the UK government to adopt P-DfMA at scale. Although many are highlighting the challenge of intellectual property, pipeline and procurement. The challenges and barriers of adopting P-DfMA require academic attention, to understand the influence of political system, history, regulations and cultural dynamics on the transformation. Currently there is not enough empirical data to show productivity improvements and to characterize the interconnections between these challenges.

The front-end challenges of P-DfMA are related to the need for continuous development of the platform. One primary challenge in product family design and platform development is the interaction with customers and the market (Simpson et al., 2006), which is the mapping of customer needs to functional requirements. For example, Johnsson (2013) highlighted the impact of the client relation for the success of platforms in construction. While the standardization in platform approaches enables an effective construction process, it also places constraints on the design, which can potentially decrease the value for the customer (Thuesen and Hvam, 2011). One of the possible concerns when using such standardized strategies to structure the activities is whether the standardization is being taken too far, thereby eliminating all creative moments in the work (Styhre and Gluch, 2010). There are other challenges that come from various aspects, such as the market segmentation, the evaluation of platform concepts, and product family positioning, etc. Therefore, in the process of platform development, dealing with such challenges through business model innovation, organizational innovation and integrated delivery is a further issue that needs to be considered. There are significant opportunities to enhance the benefits of DfMA through the development of more strategic BIM-enabled and platform-based processes that capitalize on digitization. Productivity will for example be improved through wider adoption of integrated project delivery, collaborative planning, vertical integration, digital planning and supply chain management. Evidence is also needed on how some of the most innovative configuration platforms (such as SEISMIC) are impacting the process of design and manufacture.

There are also benefits of extending BIM-enabled and platform-based DfMA digitization into the creation of smart construction sites. There is already high adoption of digitally supported site supervision and quality monitoring and clean construction practices, but there are significant opportunities for the introduction of automation/robotics, simulator videos, onsite controlled environments, equipment optimization, real-time sensors and cameras and information model links to web pages or QR codes (Lu et al., 2021). The adoption of these together is likely to bring significant productivity improvements.

The back-end challenges of P-DfMA concern the application of the platform for single projects, e.g. custom-tailored buildings. It is important to have a clear separation between the continuous development of the platform and the production based on the platform (Thuesen and Hvam, 2011). Compared with the front-end, the back-end challenges focus more on project-level issues, e.g. individual performance, rather than enterprise-level. And P-DfMA actually acts as an interface for transferring enterprise-level knowledge, resources and strategies to the project level. Through its implementation, P-DfMA transfer the enterprises' strategies of production into single projects' practices. The platform approach needs to balance the interests of both levels at the same time, because the overall product development strategy of an enterprise and the interests of a single project are sometimes not completely consistent. Generally, it is a trade-off between standardization and flexibility, which is considered as the most significant challenge in platform strategies for the construction industry (Thuesen and Hvam, 2011). According to Gibb (2001), those taking standardization seriously in the construction industry have always struggled to resolve the conflict between uniformity and variation, between maximum standardization and flexibility. Thus, construction enterprises need to further develop their integrated and systematic capabilities in terms of business model and organization innovation to harness the interface between enterprise level and project level.

The challenges will also be on the bridging of BIM and P-DfMA for the proposed vision in this chapter. There are few studies related to BIM and P-DfMA. There is limited literature available on how standardization and configuration can be applied in a BIM context to facilitate P-DfMA. In addition, needless to say that technical, legal and liability issues, building performance, building codes, standards and legislations are all challenges which can be further scrutinized as future studies and with a particular emphasis on BIM or configuration platforms or both (Piroozfar et al., 2019). As a new concept, there are still many challenges that need to be overcome by academia and industry to realize the desired vision.

7. CONCLUSIONS

This chapter reviewed previous studies about DfMA and P-DfMA, and explored their combination with BIM. It defined the concepts of DfMA, BIM and platformization and proposed a process for developing a BIM-enabled DfMA platform and concluded with implications for practice. The concept of product platform from the manufacturing industry was introduced. Potential uses of BIM-enabled P-DfMA were then explored. BIM can facilitate DfMA implementation from two perspectives. First, DfMA requires an analysis platform for identifying opportunities for improving manufacturing and assembly processes through the design. BIM provides such a platform because BIM objects can have rich information on the actual building components. The information can be used to analyse how the components will be produced and constructed, and whether DfMA principles can be applied to make the design more appropriate for production and construction. Secondly, BIM enables a seamless collaboration environment. Designers, engineers, suppliers, and constructors can use the digital model to exchange ideas and share knowledge with each other. After the design is consolidated, the BIM model can be directly sent to the suppliers or manufacturers for mass production.

Some construction and real-estate companies and institutions have begun to develop related design platforms to integrate the design of different building. But significant challenges remain. The BIM-enabled P-DfMA approach proposed by the UK government is addressing some of these challenges and is moving the discussion from projects and programmes to a wider market view. Scholarly work must further support BIM-enabled P-DfMA. This chapter has discussed implications from both practical and theoretical perspectives. From the practical perspective, incumbents and new entrants can use corresponding ways to establish DfMA and platformization strategies based on the sorted application scenarios, intelligent tools and approaches. From the theoretical perspective, this chapter introduces the product platform into BIM-enabled DfMA to promote platformization. Future theoretical research and development can be extended based on the proposed five-step framework. The chapter broadens the interaction frontiers between the manufacturing and construction industries, e.g. DfMA and product platform. And researchers and policy makers can continue to explore these frontiers in future research.

NOTE

1. 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 (RCA) and Cause and Effect Analysis (CEA) were also used as the basis of weights (Gerth et al., 2013).

ACKNOWLEDGEMENT

This chapter is based on the work of design for manufacture and assembly by Mr Tan Tan (tan.tan.17@ucl.ac.uk). Some contents of section 2 are published in peer reviewed journals and conferences, including Lu et al. (2021); Tan et al. (2020a); Tan et al. (2020b). For the copyright issues, please contact the publishing editor of the book.

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