

# Design for Manufacture and Assembly (DfMA) in construction: the old and the new

Weisheng Lu<sup>1</sup>, Tan Tan<sup>2\*</sup>, Jinying Xu<sup>3</sup>, Jing Wang<sup>4</sup>, Ke Chen<sup>5</sup>, Shang Gao<sup>6</sup>, and Fan Xue<sup>7</sup>

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## Abstract

Design for manufacture and assembly (DfMA) has become a buzzword amid the global resurgence of prefabrication and construction industrialization. Some argued that DfMA is hardly new, as there are concepts such as buildability, lean construction, value management, and integrated project delivery in place already. Others believe that DfMA is a new direction to future construction. This paper aims to review the development of DfMA in manufacturing and its status quo in construction, and clarify its similarities and differences to other concepts. A multi-step research method is adopted in this study: First, an analytical framework is generated; Secondly, a literature review is conducted on DfMA in general, and DfMA-like concepts in the AEC industry; The third step is to compare DfMA with related concepts. This study reveals that DfMA as a philosophy is hardly new in construction, and the empirical implementation of many DfMA guidelines has begun in the AEC industry. The findings suggested that DfMA is a new and mixed 'cocktail' of opportunities and challenges to improve construction productivity with the advancement of construction materials, production and assembly technologies, and ever-strengthened logistics and supply chain management. This study sheds light on three research directions: DfMA implementation and guidance strategies, DfMA frameworks and blueprints, and applications in cast in-situ or intermediate prefabrication construction. Our research findings provide a synopsis of DfMA research and development in construction. This paper can also serve as a point of departure for future theoretical and empirical explorations.

**Keywords:** Design for manufacture and assembly; Construction Industrialization; Prefabrication; Construction

<sup>1</sup> Professor, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong, e-mail: [wilsonlu@hku.hk](mailto:wilsonlu@hku.hk);

<sup>2</sup> PhD Student, Corresponding Author, The Bartlett School of Construction & Project Management, University College London, London, e-mail: [tan.tan.17@ucl.ac.uk](mailto:tan.tan.17@ucl.ac.uk), Tel.: +44(0) 77 1614 8651;

<sup>3</sup> PhD Candidate, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong, e-mail: [jinyingxu@connect.hku.hk](mailto:jinyingxu@connect.hku.hk);

<sup>4</sup> PhD Candidate, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong, e-mail: [jingww@connect.hku.hk](mailto:jingww@connect.hku.hk);

<sup>5</sup> Associate Professor, Department of Construction Management, Huazhong University of Science and Technology, e-mail: [chenkecm@hust.edu.cn](mailto:chenkecm@hust.edu.cn);

<sup>6</sup> Lecturer, Faculty of Architecture, Building and Planning, The University of Melbourne, Australia, e-mail: [shang.gao@unimelb.edu.au](mailto:shang.gao@unimelb.edu.au);

<sup>7</sup> Assistant Professor, Department of Real Estate and Construction, The University of Hong Kong, Hong Kong, e-mail: [xuef@hku.hk](mailto:xuef@hku.hk);

## 1. INTRODUCTION

Design for manufacture and assembly (DfMA) is an emerging approach in the global architecture, engineering, and construction (AEC) landscape. In 2013, the Royal Institute of British Architects (RIBA) published a *Plan of Work* for DfMA implementation. In 2016, Singapore's Building and Construction Authority (BCA) issued an official guide facilitating DfMA and its incorporation with Building Information Modeling (BIM). In 2018, the UK government's Infrastructure and Projects Authority published a revised *National Infrastructure and Construction Pipeline* detailing its preference for the Platform Method for Manufacturing and Assembly Design. The report also publicized its use for prefabrication and other offsite construction methods in public projects. The Hong Kong government's 2018 document *Construction 2.0* also emphasises the importance of DfMA. In the research realm, the DfMA literature is growing, while industry leaders such as O'Rourke (2013) and Balfour Beatty (2018) consider DfMA to be the future of construction.

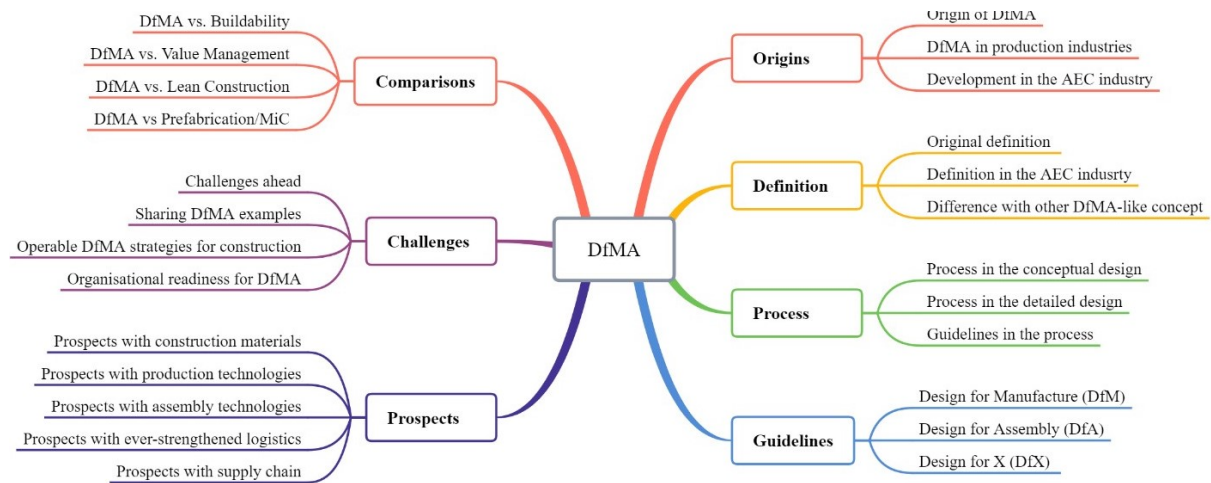
But is DfMA merely old wine in a new bottle? According to Boothroyd (2005), DfMA evaluates and improves product design by considering the downstream processes of manufacturing and assembly. Similar if not identical concepts have been introduced to improve AEC productivity and efficiency. For example, buildability assesses designs from the perspective of those who will manufacture and install components and carry out the construction work (Lam and Wong, 2009); lean construction adapts the concept of lean production/manufacturing to the AEC industry with a view to maximising value and minimizing waste (Koskela, 1992; Alarcón, 1997). Value management (VM) focuses on the early design stage and advocates achieving value for money by deliberating over functions and costs (Kelly et al., 2004; Shen and Liu, 2004), with downstream manufacturing and assembly within the critical scope of the exercise.

This paper aims to clarify the concept of DfMA in the AEC industry. First, we review the literature on its history in the manufacturing industry and current DfMA developments in construction. The research then goes on to compare DfMA with the concepts mentioned above to find their similarities and differences. Based on the review and comparisons, this study further provides prospects and challenges for DfMA. The remainder of the paper is organized as follows. Section 2 is a detailed description of the research methodology. Section 3 is an in-depth analysis of the DfMA research, while Section 4 compares DfMA with similar concepts with a view to answering the key question of this study. Section 5 articulates the prospects and challenges of DfMA, while conclusions are presented in Section 6.

## 2. METHODOLOGY

A multi-step research method consisting of brainstorming, literature review and in-depth comparative analyses is adopted in this study. First, given the long history of DfMA development, an analytical framework is required to demarcate a reasonable research boundary and guide the analyses. Since DfMA has only recently been popularized in construction, this research includes DfMA-like construction concepts (e.g., fabrication-aware design) to allow it to be fully investigated. Brainstorming, as a creative training method, can find a set of practical solutions through objective and continuous analysis of the issues discussed (Rawlinson, 2017). To establish the analytical framework for this study, an hour-long brainstorming session was held. Six researchers from different disciplines participated, all with at least six years' research experience in the AEC industry and two with around 10 years' experience in engaging with construction prefabrication in China and Hong Kong. Taking into account the possible bias of brainstorming, this step is only used to determine the scope of the discussion without having a conclusive effect on the outcome of the discussion. As a result of the session, the scope of the study was limited to seven broad DfMA-related categories: origins, definition, processes,

79 guidelines, comparisons, prospects, and challenges. The analytic framework developed is  
 80 shown in Figure 1.



82 **Figure 1** DfMA in construction: an analytic framework  
 83  
 84

85 Second, guided by this framework, a search was conducted for the relevant literature on  
 86 DfMA in general, as well as DfMA-like concepts in the AEC industry specifically, using the  
 87 bibliographic database Google Scholar. Keywords used in article selection included ‘design for  
 88 manufacture and assembly’, ‘design for manufacture’, ‘design for assembly’, ‘DfMA’,  
 89 ‘fabrication-aware design’, ‘architectural geometry’, ‘architectural design’, ‘construction’,  
 90 ‘assembly’, ‘construction industry’, and ‘AEC’. These keywords were adopted to reflect usages  
 91 across research disciplines and countries. For example, architecture researchers prefer  
 92 ‘fabrication’, while in engineering ‘manufacture’ is used to describe the building production  
 93 process. Mathematicians try to use architectural geometry to bridge the gap between complex  
 94 architectural design and applicable construction. Year of publication was limited to the period  
 95 2009 to 2019 to capture the latest DfMA research and trends in AEC. A total of 1979 results  
 96 were generated from the initial search. Then, the strict filtered process was conducted to narrow  
 97 down the scope of target articles. Articles that included related key terms in the  
 98 title/summary/keyword were considered for review, and only journal articles were selected to  
 99 ensure that all retrieved articles could be analyzed by using the same analytical structure as their  
 100 research objectives and methods. A snowball technique (Lecy and Beatty, 2012) involving  
 101 checking the references of the selected papers was applied to find relevant papers that may not  
 102 have been included. Finally, 30 publications highly related to the DfMA in the construction  
 103 were derived for the analysis of DfMA definition and research trend.

104 The third step was to develop an in-depth understanding of DfMA by comparing it with  
 105 similar concepts, such as buildability, value management, lean construction and  
 106 prefabrication/Modular integrated Construction (MiC). The literature on these concepts was  
 107 extracted and reviewed for the comparative study which mainly focused on the connotations,  
 108 extensions, and applications of the concepts and DfMA and analyzed their similarities,  
 109 differences, and linkages. These comparisons were triangulated with the past experience of the  
 110 authors involved in BIM and offsite construction in Hong Kong, China, and the UK.

### 111 3. DFMA: HISTORICAL DEVELOPMENT AND STATUS QUO

#### 112 3.1 Historical development of DfMA

113 DfMA originated during World War II when Ford and Chrysler applied it as a principle in their  
 114 weapon production processes. At first, it was used in manufacturing industry. Formal  
 115 approaches to design for manufacture (DfM) and design for assembly (DfA) emerged in the  
 116

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 thinking 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 consideration of disassembly and recycling during the design phase. Researchers are beginning to focus on the design of the environment, recyclability, life cycle, 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 (Gatenby and Foo, 1990; Kuo et al., 2001; Eastman, 2012). For example, DfX techniques can improve quality, efficiency, productivity and design flexibility, and decrease life-cycle 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 (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 happened in the construction industry. This makes it difficult to find all the information needed to apply DfX in the construction industry.

**3.2 DfMA processes and guidelines**

Researchers such as Swift and Brown (2013), Bogue (2012), and Emmatty and Sarmah (2012) have developed some guidelines for the application of DfMA, as shown in Table 1. It is a systematic procedure that helps companies make the fullest use of manufacturing and assembly processes, e.g., through emphasizing the ease of manufacture and assembly by minimizing the number of parts (Kuo et al., 2001; Eastman, 2012; Bogue, 2012). DfMA aims to determine the cost impact of those materials and processes, and finds the most efficient use of the component design (Ashley, 1995).

**Table 1.** A non-exhaustive list of DfMA guidelines

	Guidelines	Benefits
1	Aim for mistake-proof design	Avoid unnecessary re-work, improve quality, and reduce time and costs.
2	Design for ease of fabrication	Reduce time and costs by eliminating complex fixtures and tooling.
3	Design for simple part orientation and handling	Reduce time and costs by avoiding non-value adding manual effort.
4	Design with predetermined assembly techniques in mind	Reduce time and costs when assembling.

5	Consider modular designs	Reduce time and costs due to simplified design and assembly.
6	Consider design for mechanized or automated assembly	Improve assembly efficiency, quality and security.
7	Use standard and off-the-shelf components	Reduce purchasing lead time and costs.
8	Use as similar materials as possible	Reduce time with fewer manufacture processes and simplified jointing.
9	Use as environmentally friendly materials as possible	Reduce harm to the environment.
10	Minimize precast component types	Reduce time and costs with simplified design, manufacture, and assembly.
11	Minimize connector types and quantity	Reduce time and costs with simplified design, manufacture, assembly, repair and maintenance.
12	Minimize the use of fragile parts	Reduce costs due to fewer part failures, and easier handling and assembly.
13	Do not over-specify tolerances or surface finish	Reduce costs with easier manufacture.

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Sources: Swift and Brown (2013); Bogue (2012); and Emmatty and Sarmah (2012)

However, current DfMA practices in construction still, by and large, follow DfMA guidelines developed in a manufacturing context without sufficiently considering the differences between construction and manufacturing. For example, DfMA procedures in Boothroyd (2005) consider DfA and DfM but not the downstream logistics and supply chain (LSC), which plays a critical role in offsite prefabrication construction. Some construction DfMA guidelines proposed, e.g., Gbadamosi et al., (2019), Kim et al., (2016), and Banks et al. (2018), originate more or less from manufacturing-oriented guidelines. While inspiring, some of these guidelines are not necessarily a good fit with construction's characteristics, leading to an inability to improve manufacturing and assembly. Some guidelines are proposed in a fragmented fashion without necessarily forming an organic whole, leading to a lack of comprehensiveness, or "easy to use" throughout the building process. The RIBA, in recognizing the potential of DfMA in construction, added an overlay of DfMA to its time-honored Plan of Work. Following RIBA's vision (2013, p. 24), much "soft-landing" work remains to implement DfMA in construction.

Connecting general DfMA guidelines (Table 1) with the heterogeneities of the AEC industry to develop DfMA examples could inspire and encourage practitioners. Our stakeholder engagement with the industry has revealed that practitioners including clients, designers, contractors, and suppliers do explore such examples from the perspective of their separate companies. An industry-wide database of DfMA examples could increase its application. Another observation from the literature analysis and industry engagement is that we need to develop DfMA strategies operable in terms of scope, policy, procedure, and so on at company, even industry, level. RIBA's plan of work and various published DfMA blueprints are certainly meaningful points of departure. To embrace DfMA, individual companies need to work with researchers to devise such operable strategies. Frameworks and guidelines that can link general guidelines with company-specific requirements are highly desired.

### **3.3 Cross-sectoral learning**

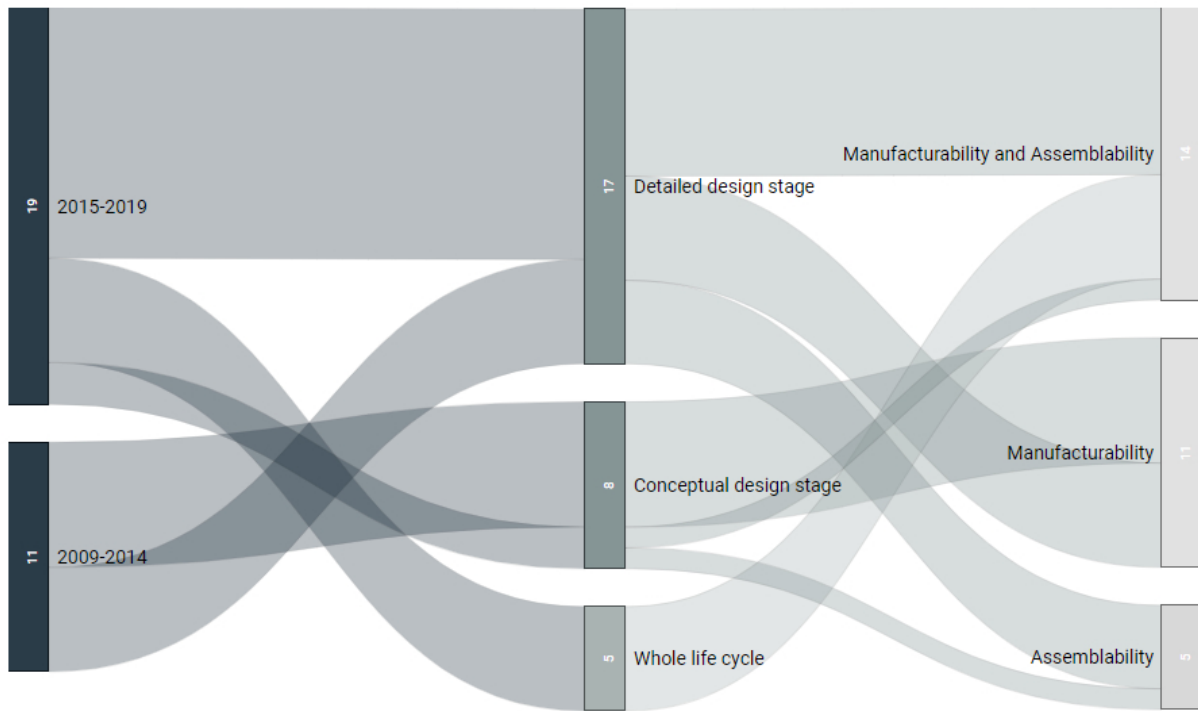
When looking at the history of DfMA in construction, scholars often cite the pioneering modernist architect Le Corbusier who, in his influential book *Towards a New Architecture* (1923), advocated industrialization of construction and proposed the famous maxim, 'A house is a machine to live in.' However, the popularity of DfMA in construction is a recent

193 phenomenon. Unlike manufactured products which are designed in-house, mass-produced, and  
194 sold to end users, construction products (e.g., housing, buildings, and infrastructure) are  
195 bespoke (Fox et al., 2001). Every construction product is contextualized within the geo-  
196 technical conditions of the site and its surroundings, the planned socio-economic function, and  
197 many other factors. There can be no ‘standard’, ‘one-size-fit-for-all’ design for mass production.  
198 It would be exceedingly difficult if not impossible for an architect, like his/her counterparts in  
199 manufacturing, to conceptualize, optimize, prototype, and select a design to mass construct. In  
200 addition, the orthodoxy dislikes the tedium of ‘standard’ architecture design. Thus, the ‘one-  
201 off’ project as an organization form has been adopted in the construction industry to organize  
202 works (Wang et al., 2018). Put simply, the construction industry looks at projects while other  
203 industries are concerned with products.

204 While construction materializes our built environment and is linked to cultural identity  
205 and civic pride (Pearce, 2003), it has long been criticized for e.g., its nuisance, poor quality  
206 (Baloi and Price, 2003), and recently, alleged low productivity (The Economist, 2017). Cross-  
207 sectoral learning has been exhorted for construction (Kao et al., 2009) but the authors of this  
208 paper incline to attribute the learning to the industry’s self-introspection and humble  
209 characteristics. The construction industry has been reinventing itself through production theory  
210 (Koskela 1992), especially through integration of design, manufacture, and assembly  
211 (Bridgewater, 1993) and lean concepts and tools for making site assembly more efficient  
212 (Tommelein, 1998). In the 2010s, government and industry documents began to include DfMA  
213 in their development plans and to illustrate its detailed definition and application in the industry.  
214 In these plans, DfMA is advocated to combine architectural design, manufacturing and on-site  
215 installation organically. The introduction of DfMA to construction industry can be understood  
216 against this cross-sectoral learning and transformation background.

### 217 218 ***3.4 Status quo of DfMA in construction***

219 The Sankey diagram shown in Figure 2 illustrates some of the research trends relating to DfMA  
220 in construction drawn from the 30 selected articles. The width of the arrows is proportional to  
221 the flow rate. The volume of this research has gradually increased over the past decade.  
222 Regarding research trends, architectural design journals tend to focus on the conceptual design  
223 stage, while engineering and construction journals focus more on the detailed design phase or  
224 the entire project life cycle. There are more articles on DfM than DfA. This may be because all  
225 types of construction involve a manufacturing process. However, assembly problems often  
226 occur in prefabricated buildings. In some architectural practices that do not fully adopt  
227 prefabrication, the idea of DfMA is nonetheless used. So although prefabrication, offsite  
228 construction, and MiC provide ideal scenarios in which to explore DfMA (Yuan et al., 2018),  
229 its applications are not constrained to these areas. DfMA can be applied in traditional cast in-  
230 situ construction. It can even be implemented as part of an on-site construction design or offsite  
231 prefabricated design (Lu et al., 2018). The degree of implementation may be the entire building,  
232 an apartment, or just a component, reflecting the emphasis of DfMA on consideration of  
233 downstream processes in order to minimize costs and maximize overall value.



**Figure 2** Sankey diagram of DfMA research in the AEC industry

A few empirical studies have begun to investigate the implementation of DfMA, mainly in offsite prefabrication and modular construction projects. As summarized in Table 2, DfMA principles have been applied to various types of construction projects for various components. For example, Kim et al. (2016) reported the use of DfMA in the selection of suitable precast beams for a highway bridge in the UK; Gerth et al. (2013) reported its application in detailing the design of light walls for two four-story houses in Sweden. These studies reveal common practices in applying DfMA, such as identifying its driver, developing criteria for ‘manufacturability’ and ‘assemblability’, investigating specific difficulties to address in design, involving different professionals in the design group, and optimizing design through various principles.

**Table 2.** A summary of construction projects applying DfMA principles

Studies	Project type	Related components	DfMA strategies
Gerth et al. (2013)	four-storey houses	light wall	<ul style="list-style-type: none"> <li>• detail the joint design</li> <li>• minimize assembly operation</li> </ul>
Kim et al. (2016)	highway bridge	precast beam	<ul style="list-style-type: none"> <li>• minimize the number of parts</li> <li>• simplify the operation</li> <li>• choose material and components</li> </ul>
Chen and Lu (2018)	high-rise commercial building	curtain wall system	<ul style="list-style-type: none"> <li>• coordinate the design of LED tubes and electric wires in the curtain wall system</li> </ul>
Banks et al. (2018)	high-rise residential and commercial tower	modularized facade, MEP system, structure, etc.	<ul style="list-style-type: none"> <li>• coordinate the facade, MEP system, and structure</li> </ul>
Peterseim et al. (2016)	new solar tower	modules of cable-stayed solar tower	<ul style="list-style-type: none"> <li>• select optimal components and materials</li> </ul>
Ramaji et al. (2017)	student dormitory	modules	<ul style="list-style-type: none"> <li>• optimize the size and geometry of parts</li> </ul>
Machado et al., (2016)	student accommodation	fittings and furnishings	<ul style="list-style-type: none"> <li>• implement BIM as a catalyst for a lean transformation, streamlining process and operations</li> </ul>

249 Previous studies have suggested different strategies for implementing DfMA, such as  
250 detailed design, minimization/simplification, and design evaluation. Detailed design entails  
251 careful planning to pre-empt issues in the manufacture and assembly stages through choice of  
252 materials/components (Kim et al., 2016), integrating different disciplines in design, such as  
253 coordinating the modular structure, façade, and mechanical, electrical and pumping (MEP)  
254 system in a high-rise building (Banks et al., 2018), or designing the LED tubing and electric  
255 wiring for a curtain wall system (Chen and Lu, 2018). Minimization/simplification emphasizes  
256 ease of manufacture and assembly through minimizing the number of parts (Kim, et al., 2016),  
257 simplifying the geometry and reducing weights of parts (Ramaji, 2017), or decreasing  
258 complexity in operations (Gerth, 2013). These strategies can directly reduce cost, time, and  
259 waste in both manufacture and assembly. In addition, evaluating engineering choices and  
260 design alternatives is also a main strategy of DfMA. Significant in this state of the art review is  
261 DfMA use for building façades (Montali et al., 2018; Montali et al., 2019; Giuda et al., 2019;  
262 Başarır and Altun, 2018), weatherproof seals (Orlowski et al., 2018), and modular components  
263 (Rausch et al., 2016). Few studies focus on design optimization of the whole built project,  
264 although some such as Yuan et al., (2018) have established a process information model for  
265 DfMA-oriented prefabricated buildings. Apart from these studies mentioned DfMA in their  
266 research, some DfMA-like concepts were studied for the improvement of manufacturability and  
267 assemblability by focusing on the design stage. For example, many studies in architecture use  
268 fabrication-aware design to represent the same idea of DfMA. Pottmann (2009; 2010; 2013)  
269 proposed architectural geometry as a design fabrication-aware design knowledge to bridge the  
270 gap between design and construction. Tepavčević et al., (2017) established a fabrication-aware  
271 design method that can be easily manufactured and assembled. These DfMA-like concepts,  
272 including fabrication-aware design and architectural geometry, also enhance manufacturability  
273 and assemblability through the early architectural design stage.

274 The construction industry has benefited from DfMA research and development in other  
275 industries. The automotive industry has explored reduction in number of parts in the assembly  
276 process. With such reduction comes decline in associated assembly operations, saving parts and  
277 operations costs (Boothroyd, 2012). When this strategy was applied in selected Swedish  
278 companies, half enjoyed up to a 33% reduction in development time and cost (Trygg, 1993). In  
279 construction, the same logic is applied in MiC, reducing parts in prefabricated modules for  
280 assembly. Another commonly adopted DfMA strategy is to establish a concurrent engineering  
281 environment. This encourages teamwork between designers, suppliers, manufacturing  
282 engineers, and any other relevant representatives in reviewing the current product  
283 manufacturing and future product design to increase productivity and reduce lead time in  
284 bringing a new product to market (Boothroyd, 2012).

## 286 4. OVERLAPS BETWEEN DFMA AND OTHER CONCEPTS

### 287 4.1 *DfMA and Buildability*

288 The concept of buildability can be traced back to the 1980s (Moore, 1996). It is defined by  
289 CIRIA (1983) as ‘the extent to which the design of a building facilitates ease of construction,  
290 subject to the overall requirements for the completed building.’ Buildability is measured on a  
291 scale from good to bad and is a criterion on which to judge the design of a building project  
292 (Wong et al., 2008. Bringing together the technical experience of builders and the design  
293 experience of architects at the design stage, it reflects architects’ awareness of construction  
294 method in the architectural design (Hyde, 1995; Wong et al., 2011). Buildable designs have  
295 improved quality and safety performance, as well as higher productivity levels, and mitigate  
296 the risks of unforeseen problems (Lam and Wong, 2011). The achievement of good buildability  
297



depends upon both designers and builders being able to see the whole construction process through each other's eyes.

In design for buildability, external factors such as geotechnical condition, access and circulation at the site, and availability of resources, skills and technology, are firstly considered to determine the most appropriate system to be used (Mbamali et al., 2005). Then, the principle of standardization, simplicity and integration or prefabrication are applied to achieve the desired level of buildability (BCA, 2000; Wong and Lam, 2008). Table 3 presents some example features of these principles. Lam and Wong (2011) further summarize nine factors of buildability: (1) allowing economic use of contractor's resources; (2) enabling design requirements to be easily visualized and coordinated by site staff; (3) enabling contractors to develop and adopt alternative construction details; (4) enabling contractors to overcome restrictive site conditions; (5) enabling standardization and repetition; (6) enabling freedom of choice between prefabricated and onsite works; (7) enabling simplification of construction details in case of non-repetitive elements; (8) minimizing the impact of adverse weather by enabling a more flexible construction program; and (9) allowing design to achieve a safe construction sequence on site.

**Table 3.** Principles of buildability and their example features

Principle	Example feature
Standardization	<ul style="list-style-type: none"> <li>◦ Repetition of grids, floor layouts, component sizes, etc.;</li> <li>◦ Modularization of grids, concrete beams, slabs, etc.;</li> <li>◦ Standardization of windows, doors, structural components, services cores, etc.</li> </ul>
Simplicity	<ul style="list-style-type: none"> <li>◦ Flat floor slabs, pre-stressed concrete flat slabs;</li> <li>◦ Simple connection details;</li> <li>◦ Simplicity in detailing.</li> </ul>
Integration/Prefabrication	<ul style="list-style-type: none"> <li>◦ Precast components such as slabs, columns, beams, façade panels, window frames, staircases, etc.;</li> <li>◦ Integrated roof system.</li> </ul>

Sources: Mbamali et al. (2005); Wong and Lam (2008)

There are perceivable similarities and differences between buildability and DfMA. First, both attempt to consider the building/manufacturing processes from the early design stage in order to ease them, as well as improve quality, cost, productivity, and safety performance. Second, both follow the standardization principle for the design of grids, layouts, structural components, doors and windows etc. Third, both encourage integration and prefabrication. However, to meet the requirement of simplicity in buildability, diversity and variability may be sacrificed; DfMA would not change or downgrade the design intentions at the cost of building particularity. Buildability can be enhanced with the implementation of DfMA, prefabrication, and virtual and automated construction technologies. DfMA is the practical implementation and optimization of quantitative and parametric design, which presents all entities in the form of components (Harik and Sahmrani, 2010; Yuan et al., 2018), and can improve buildability with the use of offsite prefabricated standardized components such as façades, bathrooms, and staircases (Gao et al., 2018). DfMA can not only focus on the design evaluation like buildability, but also implement this evaluation in the two links of manufacturing and assembly, which is especially applicable to the rise of off-site manufacturing and on-site assembly.

#### **4.2 DfMA and Value Management (VM)**

VM aims to an optimal balance of performance, cost, and time through a structured, disciplined, and team-centric problem-solving approach (Kelly et al., 2004). It has been increasingly described as the entire process to improve the value of the project from the concept stage to the

338 operation stage (Ashworth and Hogg, 2014). Both VM and DfMA have their origins in the  
339 manufacturing industry. Whereas DfMA was popularized in construction only recently, VM  
340 has been readily applied to construction for a longer period of time. In common with DfMA,  
341 VM is conducted through the integration and cooperation among multidisciplinary team  
342 members.

343 The differences between VM and DfMA are obvious. Firstly, they have different  
344 objectives. DfMA focuses on two main functionality of buildings in terms of manufacturability  
345 and assemblability whilst that of VM cares about the optimal balance and solution of all  
346 functionality and finance, not just manufacturability and assemblability. Secondly, the methods  
347 to achieve their respective goals are different. VM derives its power from being a team-based,  
348 process-driven methodology using function analysis to examine and deliver a project at  
349 optimized whole life performance and cost without detriment to quality (Male et al., 2007). A  
350 range of VM methods, such as pre-workshop info gathering, group workshop tools (e.g. Fast  
351 Diagramming, VM / design charrette), post-workshop tools and so on, is applied step by step  
352 within the context of changing project environment (Kelly and Male, 2003; Shen and Liu, 2004).  
353 In contrast, DfMA uses a series of design strategies under its guidelines and principles to  
354 achieve better manufacturability and assemblability. The main idea is to simplify and optimize  
355 the building components, connections and processes without damaging or subsiding the  
356 originally formulated functionality (Gao et al., 2019; Chen and Lu, 2018). For example,  
357 applying a digitally-designed set of components across a range of government construction  
358 programmes and projects to enhance standardization and productivity. Thus, DfMA dedicates  
359 to the improvements in the specific tectonics details of the building, such as component size,  
360 building materials and connection method, but VM starts from the perspective of architectural  
361 function and adopts a series of management methods.

362 As an optimal design philosophy, DfMA regarded as a value improvement tool can be  
363 adopted by VM. DfMA can earn value in project costs, completion time, accordance to function  
364 requirements, satisfaction of post-occupancy evaluation, and ease of maintenance (Omigbodun,  
365 2001; Newton et al., 2018). As a function-review method for optimal design, VM can be applied  
366 together with DfMA execution to enhance its cost efficiency, functionality, quality and reduce  
367 possible risks. Essentially, these two approaches differ in their focuses and methods on  
368 construction because they hold different perspectives. VM represents a project management  
369 perspective while DfMA focuses more on a product design perspective. However, they can  
370 work together to achieve more efficient construction practices.

#### 371 **4.3 DfMA and Lean Construction**

372 Lean construction is ‘a method to design production systems to minimize the waste of materials,  
373 time and efforts in order to generate the maximum possible amount of value’ (Koskela et al.,  
374 2002). It is closely linked to VM. Lean principles have their roots in Japanese manufacturing,  
375 where the supply chain was planned and optimized to reduce time, cost, and waste. Lean  
376 principles were later adapted to the construction industry with the aim of eliminating waste  
377 (Koskela, 1992) by considering the particular characteristics of construction works, such as  
378 uniqueness, complexity, and ‘one-off’ project-based production processes. Today, the focal  
379 points of lean construction are diverse, including waste elimination, strong user focus, value for  
380 money, high-quality management of projects and supply chains, and improved communications  
381 (OGC, 2000).

382 The principles of lean construction and DfMA are interrelated and mutually supportive.  
383 On the one hand, DfMA can help lean construction practices focus on reducing waste (Ohno,  
384 1988), also known as ‘non-value adding’ activities in the lean context (Koskela, 1992). It does  
385 so by assisting designers to understand what kinds of inefficient motions and operations are  
386 associated with manufacturing and assembly. This is in line with key DfMA principles, i.e.,  
387

388 minimizing the number of parts, and maximizing ease of handling and assembly (Gerth et al.,  
389 2013). Similarly, the work done by Gbadamosi et al. (2018) provides empirical evidence on  
390 how DfMA can facilitate the lean process. On the other hand, lean construction thinking can be  
391 embedded in DfMA philosophy. For example, Banks et al. (2018) considered lean supply chain  
392 management when detailing high-rise building design, while Ramaji et al. (2017) reduced the  
393 amount of assembly parts and optimized the geometry design of each part for a dormitory  
394 project. DfMA and lean principles can bring common benefits to the AEC industry, aligned to  
395 achieve maximum shared value such as reducing construction cost and efforts, and increasing  
396 construction productivity (Ogunbiyi et al., 2014).

397 The two principles, still, are conceptually different with different working scopes and  
398 focuses. Lean construction aims to eliminate construction waste, effort, and time by designing  
399 a proper production and delivery system over a supply chain. For example, flexible workforce  
400 and just-in-time are critical lean principles for preventing overstock and accelerating cash flow.  
401 Comparatively, DfMA principles work on improving ease of manufacturing and assembly from  
402 the early stage of design (Lam et al., 2009). This involves a series of measures to optimize  
403 design, but workforce flexibility and warehousing level are not as heavily involved as in lean  
404 construction.

#### 405 406 **4.4 DfMA and Prefabrication/MiC**

407 DfMA is often discussed together with prefabrication or MiC in the literature. In Gibb's (2001)  
408 widely accepted taxonomy of prefabrication adoption, Level 0 means a project does not use any  
409 form prefabrication at all, e.g. fully cast-in-situ; Level 1: Component and sub-assembly (e.g.  
410 lintels); Level 2: Non-volumetric assembly (e.g. 2-dimensional precast concrete wall panels,  
411 precast components with no usage space enclosed); Level 3: Volumetric assembly (e.g.  
412 volumetric bathrooms, kitchens with usable space enclosed); and Level 4: Modular building  
413 (e.g. 3- dimensional modules which form the fabric of the building structure). According to  
414 Tatum (1987), prefabrication shifts the conventional cast in-situ, or a part of it, to offsite  
415 specialized facilities (e.g., a precast yard) where the raw materials are used to form a component  
416 or module of the final installation. Prefabrication can be achieved by carefully designing,  
417 manufacturing, transporting and installing the construction components (Mao et al., 2013). MiC  
418 represents one specific type where free-standing integrated modules with finishes, fixtures and  
419 fittings are manufactured in a prefabrication factory and then transported to site for installation  
420 (CIC, 2019). Compared to traditional construction methods, prefabrication/MiC is competitive  
421 in reducing cost, time, and waste generated in the construction phase (Yuan et al., 2018; Tam  
422 et al., 2007).

423 The resurgence of prefabrication and construction industrialization is a response to  
424 increasing housing and construction demand around the globe. It is also an ideal scenario for  
425 promotion of DfMA. In this scenario, construction works, traditionally organized as projects,  
426 are more akin to production in the manufacturing industry. The design of prefabricated  
427 components or integrated modules generally requires more attention to make these components  
428 appropriate for offsite manufacturing and on-site assembly. DfMA can address many issues and  
429 limitations in the current construction practice. For example, in current designer-centric practice,  
430 architects may lack sufficient expertise or interest in considering problems arising at the  
431 subsequent manufacture, transportation and assembly of prefabricated components. Such  
432 expertise is usually tacit and embedded in the manufacturer's experience. Problems may include  
433 insufficient detail in prefabricated components or their connections, inappropriate split of  
434 prefabricated components, or complex component design, making reiterative design  
435 improvements in the manufacture phase difficult (Yuan et al., 2018; Jensen et al., 2008). In  
436 DfMA-oriented design, these problems can be addressed by involving manufacturers and  
437 technicians in the upfront stage (i.e., design) and carefully considering problems in subsequent

438 manufacture and assembly. Therefore, DfMA is considered as one of the most important steps  
439 in prefabrication/MiC (Jensen et al., 2008).

## 441 **5. PROSPECTS AND CHALLENGES OF DFMA**

### 442 *5.1 Prospects of DfMA*

443 DfMA is expected to have a wide range of applications, from one-off small-scale to large-scale  
444 construction projects, and can benefit both cast in-situ and prefabricated construction methods.  
445 However, its most widespread adoption is foreseen in prefabrication/MiC projects. Some  
446 empirical studies have begun to investigate the process of using DfMA guidelines for  
447 prefabrication/MiC. DfMA-oriented designs have been reported in various types of  
448 prefabrication/MiC projects around the globe. DfMA has also been applied to  
449 prefabrication/MiC using advanced information technologies such BIM (Yuan et al., 2018).  
450 Although focusing on different scenarios, these studies share some common practices in  
451 applying DfMA guidelines, e.g., forming a DfMA-oriented design team by including architects,  
452 engineers, manufacturers and contractors, identifying design problems that need to be tackled  
453 for ease of manufacture and assembly, and optimizing building design using DfMA principles.

454 The popularity of DfMA will increase with increasing demand for more integrated  
455 methods of project delivery and value creation. VM and integrated project delivery (IPD) seek  
456 to align the objectives and practices of stakeholders so that their insights can be harnessed to  
457 optimize project performance. The collaboration of stakeholders, such as designers, engineers,  
458 suppliers, and contractors at the early design stage means that more detailed information  
459 becomes available earlier than in the traditional design process. Such collaboration thus can  
460 help identify and address potential risks in the manufacturing and construction stages based on  
461 DfMA principles.

462 Another trend is the integration of DfMA and virtual design and construction (VDC)  
463 technologies like BIM. A building information model is the digital representation of a building  
464 with all building components represented by parametric objects (Eastman et al., 2011). BIM  
465 can facilitate DfMA implementation from two perspectives. First, DfMA requires an analysis  
466 platform for identifying opportunities for improving manufacturing and assembly processes  
467 through the design. BIM provides such a platform because BIM objects can have rich  
468 information on the actual building components. The information can be used to analyze how  
469 the components will be produced and constructed, and whether DfMA principles can be applied  
470 to make the design more appropriate for production and construction. Secondly, BIM enables  
471 a seamless collaboration environment. Designers, engineers, suppliers, and constructors can use  
472 the digital model to exchange ideas and share knowledge with each other (Zhong et al., 2017;  
473 Chen et al., 2017). After the design is consolidated, the BIM model can be directly sent to the  
474 suppliers or manufacturers for mass production.

475  
476 To sum up, DfMA is expected to be adopted in the AEC industry in order to improve the  
477 efficiency and effectiveness of the project delivery. Smooth deployment of DfMA principles in  
478 construction projects can be achieved with the support of new project management and delivery  
479 methods (e.g., IPD) and VDC technologies (e.g., BIM).

### 481 *5.2 Challenges Ahead*

482 The first challenge facing DfMA application in construction is lack of a suitable ecosystem that  
483 enables its widespread adoption. An ecosystem includes guidelines, standards, and affordable  
484 technologies. Guidelines and standards are important for stakeholders, especially those with  
485 less experience, to govern its procedures of DfMA applications. Additionally, a report  
486 published by O'Rourke (2013) indicates that the gross capital cost of DfMA assembly, at the  
487 early adoption stage, is comparable to that of traditional construction methods. However, if new

488 technologies were required to support DfMA applications, extra investment might be needed,  
489 making DfMA less competitive. These challenges necessitate a robust ecosystem enabling wide  
490 acceptance of DfMA.

491 Another challenge is associated with the new processes brought about by DfMA  
492 applications. DfMA requires stakeholders to shift their paradigm from conventional means of  
493 design, production, and construction (Chen and Lu, 2018; Yuan et al., 2018; Gao et al., 2019).  
494 However, it is not always easy for stakeholders to adjust to new processes. For example,  
495 designers might not be willing to accept manufacturing or construction input in their designs.  
496 The resistance to change could be considerably overwhelming. Therefore, additional efforts are  
497 necessary to manage the change, for instance, by increasing stakeholder awareness of the  
498 advantages of DfMA.

499 Furthermore, there are few cases of DfMA application in actual projects, perhaps owing  
500 to insufficient hands-on training and re-training arranged for different stakeholders to  
501 implement DfMA. Some stakeholders might choose to wait and see whether competitors  
502 implementing DfMA can receive actual benefits. Currently, a few large companies have begun  
503 to use DfMA in their projects. More successful DfMA application cases will encourage the  
504 diffusion of DfMA in the AEC industry.

## 505 **6. CONCLUSION**

506 Originating from production industries, DfMA has been hyped as a panacea for chronic  
507 problems in the AEC industry such as high cost, long delivery time, and low productivity. This  
508 paper aims to demystify the concept in AEC, which is well known for its project-based nature.  
509 Many features of AEC, e.g., bespoke requirements, ‘one-off’ endeavors, contextual  
510 embeddedness, and prolonged manufacturing and assembly lines seem to have stifled the  
511 widespread application of DfMA. Our review of the historical development of DfMA, reasons  
512 for its popularization, and its status quo development in construction, reveals that DfMA as a  
513 philosophy is hardly new in construction, and the empirical implementation of many DfMA  
514 guidelines has begun in the AEC industry.

515 A deeper look at DfMA and its similar concepts including buildability evaluation, value  
516 management, lean construction, and prefabrication/offsite construction, reveals that the DfMA  
517 philosophy is reflected in various construction practices. It further substantiated the above  
518 argument that DfMA is not entirely new in construction. Adjusting the metaphor used in our  
519 original question, however, we would argue that DfMA is a ‘new cocktail in a new bottle’.  
520 Bearing a set of well-developed DfMA guidelines, it embraces a variety of tools and techniques,  
521 such as BIM, VDC, MiC, prefabrication, IoTs, and smart construction, to help designers  
522 optimize design, manufacturing, and assembly. It is also compatible with prevailing concepts  
523 in construction, such as integrated procurement models (e.g., design and building, IPD), pre-  
524 occupational evaluation, value management, and lean construction to enhance value in the AEC  
525 industry.

526 Nevertheless, DfMA in construction is still in its infancy. Current research and practice  
527 of DfMA in the construction industry largely follow some guidance and strategies of the  
528 manufacturing industry, without fully considering their differences. Some of these strategies,  
529 frameworks, and applications are inadequate for the construction industry, especially in projects  
530 with varying degrees of prefabrication. Practitioners need to be inspired and encouraged by  
531 successful DfMA examples, for which a sharing platform across the globe is required. The  
532 limited examples reported in the literature give the impression that DfMA serves  
533 prefabrication/MiC only. More research studies on its applications in cast in-situ, or  
534 intermediate prefabrication construction are recommended. In addition to encouraging DfMA  
535 frameworks and blueprints already developed in various countries, operable strategies are  
536 needed to guide interested stakeholders in implementing DfMA in their respective businesses.  
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## REFERENCES

- Alarcón, L. (1997). *Lean construction*. CRC Press.
- Ashley, S. (1995). Cutting costs and time with DfMA. *Mechanical Engineering*, 117(3), 74.
- Ashworth, A., & Hogg, K. (2014). *Added value in design and construction*. Routledge.
- Baloi, D., & Price, A. D. (2003). Modelling global risk factors affecting construction cost performance. *International journal of project management*, 21(4), 261-269.
- Balfour Beatty (2018). *Streamlined construction: Seven steps to offsite and modular building*.
- Banks, C., Kotecha, R., Curtis, J., Dee, C., Pitt, N., & Papworth, R. (2018). Enhancing high-rise residential construction through design for manufacture and assembly—a UK case study. *Proceedings of the Institution of Civil Engineers-Management, Procurement and Law*, 171(4), 164-175.
- Başarır, B., & Altun, C. M. (2018). A Redesign Procedure to Manufacture Adaptive Façades with Standard Products. *Journal of Facade Design and Engineering*, 6(3), 77-100.
- BCA (2000). *Code of practice on buildable design*. Building and Construction Authority, Singapore.
- BCA (2016). *BIM for DfMA Essential Guide*. Building and Construction Authority, Singapore.
- Bogue, R. (2012). Design for manufacture and assembly: background, capabilities and applications. *Assembly Automation*, 32(2), 112-118.
- Boothroyd, G. (2005). *Assembly automation and product design*. CRC Press.
- Boothroyd, G (2012). Design For Manufacture And Assembly: The Boothroyd-Dewhurst Experience. In Eastman, C. M. (Ed.). *Design for X: concurrent engineering imperatives*. (pp. 19-40). Springer Science & Business Media.
- Bridgewater, C. (1993). Principles of design for automation applied to construction tasks. *Automation in Construction*, 2(1), 57-64.
- Chen, K., & Lu, W. (2018). Design for manufacture and assembly oriented design approach to a curtain wall system: A case study of a commercial building in Wuhan, China. *Sustainability*, 10(7), 2211.
- Chen, K., Xu, G., Xue, F., Zhong, R. Y., Liu, D., & Lu, W. (2017). A physical Internet-enabled BIM system for prefabricated construction. *International Journal of Computer Integrated Manufacturing*. 31(4-5), <https://bit.ly/2PLRAM3>.
- Construction Industry Council (CIC) (2019). What is CIC? Available at <https://bit.ly/2vBWLVI>.
- Construction Industry Research and Information Association (CIRIA) (1983). *Buildability: an assessment*. London: CIRIA.
- Di Giuda, G. M., Giana, P. E., Masera, G., Seghezzi, E., & Villa, V. (2019). A BIM-based approach to façade cladding optimization: geometrical, economic, and production-control in a DfMA perspective. In *2019 European Conference on Computing in Construction (Vol. 1, pp. 324-331)*. European Council on Computing in Construction.
- Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. John Wiley & Sons.
- Eastman, C. M. (2012). *Design for X: concurrent engineering imperatives*. Springer Science & Business Media.
- Emmatty, F. J., & Sarmah, S. P. (2012). Modular product development through platform-based design and DfMA. *Journal of Engineering Design*, 23(9), 696-714.
- Fox, S., Marsh, L., & Cockerham, G. (2001). Design for manufacture: a strategy for successful application to buildings. *Construction Management and Economics*, 19(5), 493-502.
- Gao, S., Low, S. P., & Nair, K. (2018). Design for manufacturing and assembly (DfMA): a preliminary study of factors influencing its adoption in Singapore. *Architectural Engineering and Design Management*, 14(6), 440-456.

- 588 Gao, S., Jin, R., & Lu, W. (2019). Design for manufacture and assembly in construction: a  
589 review. *Building Research & Information*, 1-13.
- 590 Gatenby, D. A., & Foo, G. (1990). Design for X (DFX): Key to competitive, profitable  
591 products. *AT&T Technical Journal*, 69(3), 2-13.
- 592 Gbadamosi, A. Q., Mahamadu, A. M., Manu, P., Akinade, O., Sierra, F., Lam, T. T., &  
593 Alzaatreh, A. (2018). A BIM based approach for optimization of construction and  
594 assembly through material selection. In: Skibniewski, M. and Hajdu, M., eds. Creative  
595 Construction Conference 2018 (CCC 2018), Ljubljana, Slovenia, 30 June - 3 July 2018.
- 596 Gerth, R., Boqvist, A., Bjelkemyr, M., & Lindberg, B. (2013). Design for construction: utilizing  
597 production experiences in development. *Construction Management and Economics*,  
598 31(2), 135-150.
- 599 Gibb, A. G. (2001). Standardization and pre-assembly-distinguishing myth from reality using  
600 case study research. *Construction Management and Economics*, 19(3), 307-315.
- 601 Harik, R. F., & Sahmrani, N. (2010). DFMA+, a quantitative DFMA methodology. *Computer-  
602 Aided Design and Applications*, 7(5), 701-709.
- 603 Huang, G. Q. (2012). Introduction. In Eastman, C. M. (Ed.). Design for X: concurrent  
604 engineering imperatives. (1-18). Springer Science & Business Media.
- 605 Hyde, R. (1995). Buildability as a design concept for architects: a case study of laboratory  
606 buildings. *Engineering, Construction and Architectural Management*, 2(1), 45-56.
- 607 Infrastructure and Projects Authority (2018). *National infrastructure and construction pipeline*.  
608 Available at <https://bit.ly/2QoJxYn>.
- 609 Jensen, P., Olofsson, T., Sandberg, M., & Malmgren, L. (2008). Reducing complexity of  
610 customized prefabricated buildings through modularization and IT support.  
611 In *International Conference on Information Technology in Construction: 15/07/2008-  
612 17/07/2008* (429-437). Universidad de Talca.
- 613 Kao, C. C., Green, S. D., & Larsen, G. D. (2009). Emergent discourses of construction  
614 competitiveness: localized learning and embeddedness. *Construction Management and  
615 Economics*, 27(10), 1005-1017.
- 616 Kelly, J., Male, S., Graham, D., Male, S., & Graham, D. (2004). *Value management of  
617 Construction Projects* (pp. 9-19). Oxford: Blackwell Science.
- 618 Kelly, J., & Male, S. (2003). *Value management in design and construction*. Routledge.
- 619 Kim, M. K., McGovern, S., Belsky, M., Middleton, C., & Brilakis, I. (2016). A suitability  
620 analysis of precast components for standardized bridge construction in the United  
621 Kingdom. *Procedia Engineering*, 164, 188-195.
- 622 Koskela, L. (1992). *Application of the new production philosophy to construction* (Vol. 72).  
623 Stanford: Stanford University.
- 624 Koskela, L., Howell, G., Ballard, G., & Tommelein, I. (2002). The foundations of lean  
625 construction. *Design and construction: Building in Value*, 291, 211-226.
- 626 Kuo, T. C., Huang, S. H., & Zhang, H. C. (2001). Design for manufacture and design for 'X':  
627 concepts, applications, and perspectives. *Computers & Industrial Engineering*, 41(3),  
628 241-260.
- 629 Lam, P. T., & Wong, F. W. (2009). Improving building project performance: how buildability  
630 benchmarking can help. *Construction Management and Economics*, 27(1), 41-52.
- 631 Lam, P. T., & Wong, F. W. (2011). A comparative study of buildability perspectives between  
632 clients, consultants and contractors. *Construction Innovation*, 11(3), 305-320.
- 633 Lecy, J. D., & Beatty, K. E. (2012). Representative literature reviews using constrained  
634 snowball sampling and citation network analysis. Available at SSRN 1992601.
- 635 Lu, W., Chen, K., Xue, F., & Pan, W. (2018). Searching for an optimal level of prefabrication  
636 in construction: An analytical framework. *Journal of Cleaner Production*, 201, 236-245.

- 637 Machado, M., Underwood, J., & Fleming, A. (2016). Implementing BIM to streamline a design,  
638 manufacture, and fitting workflow: a case study on a fit-out SME in the UK. *International*  
639 *Journal of 3-D Information Modeling (IJ3DIM)*, 5(3), 31-46.
- 640 Male, S., Kelly, J., Gronqvist, M., & Graham, D. (2007). Managing value as a management  
641 style for projects. *International Journal of Project Management*, 25(2), 107-114.
- 642 Mao, C., Shen, Q., Shen, L., & Tang, L. (2013). Comparative study of greenhouse gas emissions  
643 between offsite prefabrication and conventional construction methods: Two case studies  
644 of residential projects. *Energy and Buildings*, 66, 165-176.
- 645 Maskell, B. H. (1991). *Performance measurement for world class manufacturing: A model for*  
646 *American companies*. CRC press.
- 647 Mbamali, I., Aiyetan, O. A., & Kehinde, J. O. (2005). Building design for buildability: an  
648 investigation of the current practice in Nigeria. *Building and Environment*, 40(9), 1267-  
649 1274.
- 650 Montali, J., Overend, M., Pelken, P. M., & Sauchelli, M. (2018). Knowledge-Based  
651 Engineering in the design for manufacture of prefabricated façades: current gaps and  
652 future trends. *Architectural Engineering and Design Management*, 14(1-2), 78-94.
- 653 Montali, J., Sauchelli, M., Jin, Q., & Overend, M. (2019). Knowledge-rich optimisation of  
654 prefabricated façades to support conceptual design. *Automation in Construction*, 97, 192-  
655 204.
- 656 Moore, D. (1996). Buildability assessment and the development of an automated design aid for  
657 managing the transfer of construction process knowledge. *Engineering, Construction and*  
658 *Architectural Management*, 3(1/2), 29-46.
- 659 Newton, C., Backhouse, S., Aibinu, A., Cleveland, B., Crawford, R., Holzer, D., ... & Kvan, T.  
660 (2018). Plug n Play: Future Prefab for Smart Green Schools. *Buildings*, 8(7), 88.
- 661 OGC (2000), Achieving Sustainability in Construction Procurement, Produced by the  
662 Sustainability Action Group of the Government Construction Clients' Panel (GCCP),  
663 available at: [www.ogc.gov.uk/documents/Sustainability\\_in\\_Construction\\_](http://www.ogc.gov.uk/documents/Sustainability_in_Construction_Procurement.pdf)  
664 [Procurement.pdf](http://www.ogc.gov.uk/documents/Sustainability_in_Construction_Procurement.pdf)
- 665 Ogunbiyi, O., Goulding, J. S., & Oladapo, A. (2014). An empirical study of the impact of lean  
666 construction techniques on sustainable construction in the UK. *Construction*  
667 *Innovation*, 14(1), 88-107.
- 668 Ohno, T. (1988). *Toyota production system: beyond large-scale production*. crc Press.
- 669 Omigbodun, A. (2001). Value engineering and optimal building projects. *Journal of*  
670 *Architectural Engineering*, 7(2), 40-43.
- 671 Orłowski, K., Shanaka, K., & Mendis, P. (2018). Design and Development of Weatherproof  
672 Seals for Prefabricated Construction: A Methodological Approach. *Buildings*, 8(9), 117.
- 673 O'Rourke, L. (2013). The future of DfMA is the future of construction. *Engineering Excellence*  
674 *Journal* (2013), 77.
- 675 Pearce, D. W. (2003). *The Social and Economic Value of Construction: The Construction*  
676 *Industry's Contribution to Sustainable Development, 2003*. Construction Industry  
677 Research and Innovation Strategy Panel.
- 678 Peterseim, J. H., White, S., & Hellwig, U. (2016). Novel solar tower structure to lower plant  
679 cost and construction risk. In *AIP Conference Proceedings*, 1734(1), p. 070025). AIP  
680 Publishing.
- 681 Pottman, H. (2009). Geometry and new and future spatial patterns. *Architectural Design*, 79(6),  
682 60-65.
- 683 Pottmann, H. (2010). Architectural geometry as design knowledge. *Architectural Design*, 80(4),  
684 72-77.
- 685 Pottmann, H. (2013). Architectural geometry and fabrication-aware design. *Nexus Network*  
686 *Journal*, 15(2), 195-208.



- 687 Ramaji, I. J., Memari, A. M., & Messner, J. I. (2017). Product-oriented information delivery  
688 framework for multistory modular building projects. *Journal of Computing in Civil*  
689 *Engineering*, 31(4), 04017001.
- 690 Rawlinson, J. G. (2017). *Creative Thinking and Brainstorming*. Routledge.
- 691 Royal Institute of British Architects. (2013), *RIBA Plan of Work 2013*. RIBA Publishing.
- 692 Shen, Q., & Liu, G. (2004). Applications of value management in the construction industry in  
693 China. *Engineering, Construction and Architectural Management*, 11(1), 9-19.
- 694 Swift, K. G., & Brown, N. J. (2013). Implementation strategies for design for manufacture  
695 methodologies, Proceedings of the Institution of Mechanical Engineers. *Part B: Journal*  
696 *of Engineering Manufacture*, 217(6), 827–833.
- 697 Tam, V. W., Tam, C. M., Zeng, S. X., & Ng, W. C. (2007). Towards adoption of prefabrication  
698 in construction. *Building and Environment*, 42(10), 3642-3654.
- 699 Tatum, C. B., Vanegas, J. A., & Williams, J. M. (1987). *Constructability improvement using*  
700 *prefabrication, preassembly, and modularization*. Austin, TX, USA: Bureau of  
701 Engineering Research, University of Texas at Austin.
- 702 Tepavčević, B., Stojaković, V., Mitov, D., Bajšanski, I., & Jovanović, M. (2017). Design to  
703 fabrication method of thin shell structures based on a friction-fit connection system.  
704 *Automation in Construction*, 84, 207-213.
- 705 The Economist (2017). The construction industry's productivity problem [Electronic Version].  
706 *The Economist*. <https://econ.st/2RzMkLW>, retrieved on April 03, 2019.
- 707 The Government of Hong Kong SAR Development Bureau. (2018). *Construction 2.0*.  
708 Available at <https://www.hkc2.hk/booklet/Construction-2-0-en.pdf>
- 709 Tommelein, I. D. (1998). Pull-driven scheduling for pipe-spool installation: Simulation of lean  
710 construction technique. *Journal of Construction Engineering and Management*, 124(4),  
711 279-288.
- 712 Trygg, L. (1993). Concurrent engineering practices in selected Swedish companies: a  
713 movement or an activity of the few?. *Journal of Product Innovation Management*, 10(5),  
714 403-415.
- 715 Wong, F. W., & Lam, P. T. (2008). Benchmarking of buildability and construction performance  
716 in Singapore: is there a case for Hong Kong?. *International Journal of Construction*  
717 *Management*, 8(1), 1-27.
- 718 Wang, H.D. Lu, W., Sönderland, J., & Chen, K. (2018). The interplay between formal and  
719 informal institutions in projects: A social network analysis. *Project Management Journal*,  
720 49(4) 20–35.
- 721 Yuan, Z., Sun, C., & Wang, Y. (2018). Design for Manufacture and Assembly-oriented  
722 parametric design of prefabricated buildings. *Automation in Construction*, 88, 13-22.
- 723 Zhong, R., Peng, Y., Xue, F., Fang, J., Zou, W., Luo, H., Ng, S.T., Lu, W.S., Shen, Q.P., and  
724 Huang, G.Q. (2017). Prefabricated construction enabled by the Internet-of-  
725 Things. *Automation in Construction*, 76(4), 59–70.
- 726