

# 1 Construction-Oriented Design for Manufacture and Assembly (DfMA)

## 2 Guidelines

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## 6 Abstract

7 The pursuit of modern product sophistication and production efficiency has bolstered Design  
8 for Manufacture and Assembly (DfMA) around the world. Being both a design philosophy and  
9 a methodology, DfMA has existed in manufacturing for decades. It is coming into vogue in  
10 construction as a potential solution to the industry's lackluster productivity amid enduring  
11 exhortation of cross-sectoral learning. However, many studies of DfMA in construction are still  
12 simply following the DfMA guidelines developed from manufacturing without adequately  
13 considering important differences between the two sectors of construction and manufacturing.  
14 This study aims to develop a series of construction-oriented DfMA guidelines by adopting a  
15 mixed-method approach. It critiques existing DfMA guidelines in relation to the characteristics  
16 of construction, and further argues that construction-oriented DfMA should consider five  
17 fundamental aspects: contextual basis, technology rationalization, logistics optimization,  
18 component integration, and material-lightening, either individually or collectively. A case study  
19 is then conducted to substantiate and verify the feasibility of these guidelines. This research  
20 sheds new light on the cross-sectoral learning of DfMA from manufacturing to construction.  
21 The guidelines can be used as the benchmark for the evaluation of manufacturability and  
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23 assemblability in practice. It also opens up a new avenue for further DfMA studies in  
24 construction.

25  
26 **Keywords:** Design for manufacture and assembly; Architecture; Construction; Manufacturing;  
27 Assembly; Design guidelines

## 28 29 **Introduction**

30 Design for Manufacturing and Assembly (DfMA) is both a design philosophy and methodology  
31 whereby the downstream processes of manufacturing and assembly are considered when  
32 designing products (Boothroyd, 2005). Originating from the manufacturing industry, DfMA  
33 suggests a systematic design process that integrates the production experience into the product  
34 design (Corbett et al., 1991; Kuo et al., 2001; Harik and Sahmrani, 2010). It has two components:  
35 design for manufacture (DfM) and design for assembly (DfA). DfM compares selected  
36 materials and manufacturing processes for the parts, determines the cost impact of those  
37 materials and processes, and finds the most efficient use of the component design (Ashley,  
38 1995), while DfA addresses the means of assembling the parts (Bogue, 2012). Altogether,  
39 DfMA represents a shift from a traditional, sequential approach to a non-linear, reiterative  
40 design methodology. Since its emergence during World War II and flourishing in the  
41 1960s~1970s, numerous DfMA guidelines (e.g., Boothroyd, 2005; Swift and Brown, 2013;  
42 Bogue, 2012; Emmatty and Sarmah, 2012) have been developed to help designers to operate  
43 this design philosophy to improve designs, productivity and profitability (Gatenby and Foo,  
44 1990; Kuo et al., 2001). More recently, a ‘Design for Excellence’ (DfX) approach has  
45 developed where the ‘X’ may denote excellence in any aspect, including testability, compliance,  
46 reliability, manufacturability, inspection, variability, and cost (Maskell, 2013; Huang, 2012).

47  
48 DfMA is now beginning to come into vogue in the construction industry. Notably, the Royal  
49 Institute of British Architects (RIBA) (2013) published a DfMA overlay to its *Plan of Work*  
50 *2013*. The governments of the UK, Singapore, and Hong Kong have all published DfMA guides  
51 or emphasized its importance in construction. Industry giants such as a Laing O’Rourke (2013)  
52 and Balfour Beatty (2018) have even indicated that they consider DfMA to be the future of  
53 construction.

54  
55 Some terminologies need to be clarified here. According to Dainty et al. (2007), precisely what  
56 constitutes construction is subject to a range of boundary definitions. There are narrow and  
57 broad definitions of construction (Pearce, 2003). The narrow definition of construction focuses  
58 on onsite assembly and the repair of buildings and infrastructure. Contrastingly, the broad  
59 definition of construction could include quarrying of raw materials, manufacture of building  
60 materials, sale of construction products (Dainty et al., 2007), and professional services such as  
61 architectural design, urban planning, landscape architecture, engineering design, surveying,  
62 construction-related accountancy, and legal services (Jewell et al., 2014). All the above sub-

63 sectors can be allocated a four-digit U.S. SIC (Standard Industrial Classification) code, which  
64 is in accordance with the United Nation’s International SIC or the U.K. SIC (Lu et al., 2013).  
65 At the risk of oversimplification, this study treats upstream architecture and engineering  
66 activities as “design”, and downstream onsite activities as “construction”. Onsite construction  
67 is traditionally conducted using cast in-situ; it is a combination of fabrication and assembly  
68 (Ballard and Howell, 1998). In recent years, the global construction industry has seen a number  
69 of initiatives to minimize onsite construction, shifting it to downstream offsite  
70 “manufacture”/fabrication but bringing it back onsite for “assembly” (Duncan in RIBA 2013).  
71 To understand the concept of DfMA in construction, one must position it in the heterogeneous  
72 context of construction and be cognizant of the relationships between architecture, engineering,  
73 construction, manufacturing, and assembly therein.

74  
75 One can also understand the DfMA trend against the background of global construction, which  
76 is characterized by ever-heightened product sophistication, sluggish productivity growth,  
77 increasing influence of cross-sectoral learning, and emerging technological advancements in  
78 virtual design and construction. Production inefficiency in construction has been criticized in a  
79 succession of influential UK-based industry reports, including ‘Constructing the Team’  
80 (Latham, 1994), ‘Rethinking Construction’ (Egan, 1998), ‘Never Waste a Good Crisis’  
81 (Wolstenholme et al., 2009), and more recently in *The Economist* (2017) comparing  
82 construction productivity with its manufacturing and agriculture counterparts. Construction has  
83 been accused of being ‘adversarial’, ‘ineffective’, ‘fragmented’, and ‘incapable of delivering’,  
84 with an appalling backwardness that should be improved, e.g., through industrial structure or  
85 organizational culture. Increasingly, it is exhorted that construction should look to and learn  
86 from highly productive industries such as advanced manufacturing (Camacho et al., 2018).  
87 Lean construction (Koskela, 1992) is typically advocated as a result, as is DfMA.

88  
89 The exploration of production innovation, in particular offsite construction, has provided an  
90 unprecedented opportunity for DfMA. It is the similarities between offsite  
91 construction/prefabrication and manufacturing that have pushed DfMA to the fore of the  
92 industry’s cross-sectoral learning and innovation agenda. In addition, emerging technological  
93 advancements, such as Building Information Modelling (BIM), 3D printing, the Internet of  
94 Things (IoTs), and robotics provide the construction industry, DfMA in particular, new entry  
95 points for manufacturing knowledge and efficiency improvement.

96  
97 However, current DfMA practices in construction still, by and large, follow DfMA guidelines  
98 developed in a manufacturing context without sufficiently considering the differences between  
99 construction and manufacturing. For example, DfMA procedures in Boothroyd (2005) consider  
100 DfA and DfM but not the downstream logistics and supply chain (LSC), which plays a critical  
101 role in offsite prefabrication construction. Some construction DfMA guidelines proposed, e.g.,  
102 Gbadamosi et al., (2019), Kim et al., (2016), and Banks et al. (2018), originate more or less

103 from manufacturing-oriented guidelines. While inspiring, some of these guidelines are not  
104 necessarily a good fit with construction's characteristics, leading to an inability to improve  
105 manufacturing and assembly. Some guidelines are proposed in a fragmented fashion without  
106 necessarily forming an organic whole, leading to a lack of comprehensiveness, or "easy to use"  
107 throughout the building process. The RIBA, in recognizing the potential of DfMA in  
108 construction, added an overlay of DfMA to its time-honored *Plan of Work*. Following RIBA's  
109 vision (2013, p. 24), much "soft-landing" work remains to implement DfMA in construction.

110  
111 Partly responding to this call for "soft-landing" work, this paper aims to facilitate the  
112 implementation of DfMA in construction by proposing a series of construction-oriented DfMA  
113 guidelines. It has three objectives: (1) to identify the differences between manufacturing and  
114 construction; (2) to propose a series of construction-oriented DfMA guidelines; and (3) to  
115 evaluate the proposed DfMA guidelines by using empirical evidence. These objectives are  
116 achieved using a mixed-method approach including literature review, comparative analysis, and  
117 case study. The remainder of this paper is organized into six sections. Section 2 presents basic  
118 knowledge such as the origin, concept, and general applications of DfMA. Section 3 describes  
119 the research methods adopted. Section 4 introduces the development of DfMA guidelines for  
120 construction projects by adapting existing DfMA guidelines to fit the characteristics of the  
121 design process and the final product in construction. In Section 5, the developed DfMA  
122 guidelines are evaluated through empirical evidence from research and practice. The last two  
123 sections present discussions and a conclusion, respectively.

## 124 125 **An overview of Design for Manufacture and Assembly**

126 DfMA originated in the weapon production processes developed by Ford and Chrysler during  
127 World War II. Formal approaches to DfM and DfA emerged in the late 1960s and early 1970s  
128 when the UK published *The Management of Design for Economic Production* standard in 1975.  
129 The academic exploration of DfMA can be traced back to the 1970s when Boothroyd and  
130 Dewhurst conducted research and practice in this area. Boothroyd (1994) described the  
131 shortcomings of an "over the wall" design approach and suggests the application of DfMA  
132 methodology to making production knowledge available to designers. Hamidi and Farahmand  
133 (2008) suggested that DfMA implementation needs a feedback loop between design and  
134 manufacturing; for example, with a design being checked by the manufacturer to identify  
135 potential problems or waste in the downstream processes of manufacturing and assembly.

136  
137 Since its adoption in manufacturing, DfMA has helped many companies increase their profits  
138 through optimized design (Gatenby and Foo, 1990; Kuo et al., 2001). Several guidelines have  
139 been consolidated to help designers reduce difficulties in manufacturing and assembling a  
140 product. Examples include minimizing the number of parts (Kuo et al., 2001; Eastman, 2012;  
141 Bogue, 2012) and searching for the most efficient use of modular design (Ashley, 1995). Some  
142 analytical tools have also been developed for designers to evaluate their proposed design from

143 the perspectives of manufacturing and assembly difficulties. Although these  
144 guidelines/principles have been developed from various reference points, they share substantial  
145 similarities, with minimization, standardization, and modular design emerging as key DfMA  
146 principles.

147

148 The importance of considering the production process in the design stage is also recognized by  
149 the construction industry. Architectural and engineering design have never been a pure art; there  
150 is a long-standing architectural philosophy of “form follows function” (Goulding et al., 2015)  
151 whereby form, functions, quantity, and buildability should be considered in design. Design  
152 optimization has been advocated. But DfMA is different in that it consciously highlights the  
153 downstream processes of manufacturing and assembly. With its success in the manufacturing,  
154 civil aviation, auto, and other industries, researchers have suggested the implementation of  
155 DfMA in construction to harvest benefits including time reduction, cost minimization, and  
156 achieving customer satisfaction. Although DfMA has only recently been introduced to  
157 construction, some DfMA-like thinking precedes it. For example, Fox et al. (2001) proposed a  
158 strategy for DfM application to buildings, and Crowther (1999) proposed design for  
159 disassembly as the final step of DfA in construction for life cycle assemblability. More recently,  
160 Yuan et al. (2018) integrated BIM and DfMA to develop the concept and process of DfMA-  
161 oriented parametric design, and Arashpour et al. (2018) explained DfMA guidelines in modular  
162 prefabrication of complex façade systems. Chen and Lu (2018) also highlighted the application  
163 of DfMA in the façade system through a case study. In addition to this research work, industrial  
164 reports such as Laing O’Rourke (2013), Balfour Beatty (2018), and RIBA’s DfMA overlay  
165 (2013) have helped popularize DfMA in construction.

166

167 Despite support from both academia and industry, DfMA has yet to achieve fervent  
168 implementation in construction because of problems related to new design system and  
169 standardization, fragmentation, multi-party coordination, and lack of proper design guidelines  
170 (Jin et al., 2018; Gao et al., 2018). Few studies, if any, have discussed the differences of DfMA's  
171 guidelines between manufacturing and construction. Indiscriminate introduction of guidelines  
172 from a manufacturing to construction may not increase productivity, and will definitely pose  
173 additional uncertainties and risks (Paez et al. 2005).

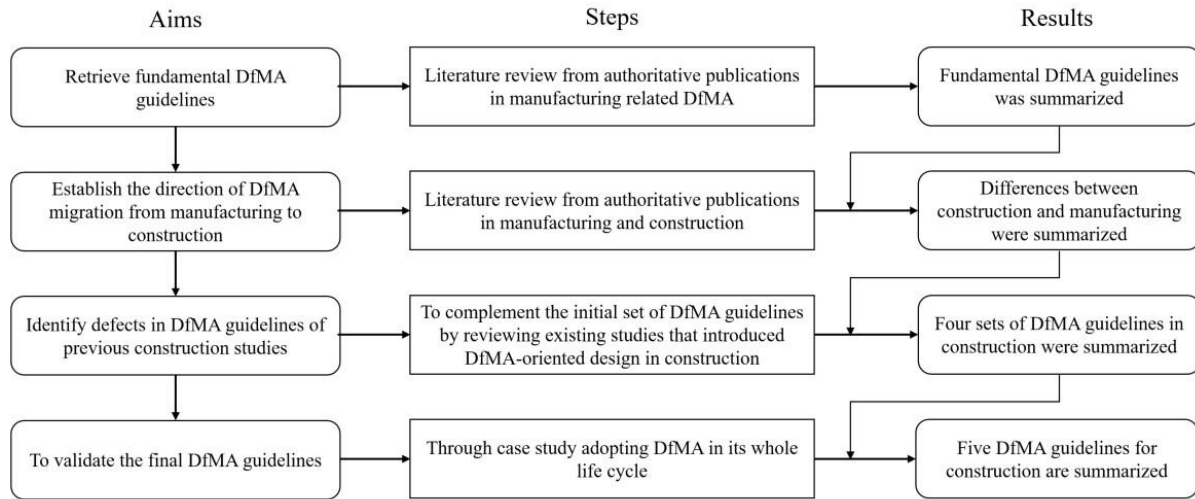
174

## 175 **Research methods**

176 This study adopts a four-step research design, as shown in Figure 1. The first step is to review  
177 fundamental guidelines of DfMA widely adopted in the manufacturing industry. These  
178 guidelines are retrieved from authoritative publications, including academic papers and reports.  
179 Some of these guidelines can be applied to the design of building components for efficient  
180 construction, but others cannot. Therefore, the second step is to generate a tentative set of DfMA  
181 guidelines applicable to construction. This process is delivered based on an understanding of  
182 the similarities and differences between construction and manufacturing. The third step is to

183 complement the tentative DfMA guidelines by analyzing construction projects that have  
 184 pioneered DfMA-oriented design. The set of DfMA guidelines will be further validated in the  
 185 fourth and final step of this study.

186



187

188 **Fig. 1.** Research design and methods

189

190 Three principles underpin the transplantation of DfMA guidelines from manufacturing to  
 191 construction. The first is to reduce inappropriate guidelines and merge or amend vague  
 192 guidelines. Some guidelines that cannot meet the production requirements of construction due  
 193 to its unique characteristics will be deleted. Guidelines that are too vague or not amenable to  
 194 accurate and efficient implementation will be re-organized or re-presented. The second  
 195 principle is to increase applicable guidelines in line with the unique characteristics of  
 196 construction. Manufacturing-oriented DfMA guidelines may not fully describe the needs of  
 197 manufacturability and assemblability in construction projects. Properly enhanced, these DfMA  
 198 guidelines, however, can provide decision-makers with adequate design options. The third  
 199 principle is to establish DfMA guidelines using a systems theory lens. Many DfMA guidelines  
 200 developed from the manufacturing industry are, in fact, appropriate only from a micro  
 201 perspective. Using these guidelines discretely without systematic consideration might not  
 202 increase manufacturability and assemblability in real-life construction projects.

203

## 204 **Towards construction-oriented DfMA guidelines**

### 205 *DfMA guidelines for manufacturing*

206 DfMA signifies a shift in traditional, sequential design thinking to a non-linear, reiterative  
 207 methodology by actively considering the downstream processes in the upfront design stage.  
 208 Researchers such as Stoll (1986), Swift and Brown (2013), Bogue (2012), and Emmatty and  
 209 Sarmah (2012) provided some key guidelines for the application of DfMA in manufacturing,  
 210 as shown in Table 1. Their focal points are mainly related to design, fabrication, assembly, and  
 211 materials. From Table 1, it is clear that simplification and the assembly process are spotlighted.  
 212 The guidelines are descriptive and qualitative, with no quantitative, implementable, and

213 numerical details that are easy to comprehend and execute. While some of the principle aspects  
 214 are relevant to construction, the guidelines when proposed did not necessarily consider the  
 215 heterogeneity of construction.

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

	Guidelines	Perspectives	Benefits	Reference
1	Aim for mistake-proof design	SD	Avoids unnecessary re-work, improve quality, reduce time and costs	①; ②; ③; ④
2	Design for ease of fabrication	F; SP	Reduces time and costs by eliminating complex fixtures and tooling	①; ②; ④
3	Design for simple part orientation and handling	F; SP	Reduces time and costs by avoiding non-value adding manual effort	①; ②; ④
4	Design with a predetermined assembly technique in mind	F	Reduces time and costs when assembling	①; ④
5	Design multifunctional and multi-use parts	F; SP; SD	Reduces time with fewer manufacture processes and simplified jointing	②
6	Consider modular designs	SP; M	Reduces time and costs due to simplified design and assembly	①; ②; ③; ④
7	Consider design for mechanized or automated assembly	SP; A	Improves assembly efficiency, quality, and security	①; ③; ④
8	Use standard and off-the-shelf components	SP; M; SD	Reduces purchasing lead time and costs	①; ②; ③; ④
9	Use as similar materials as possible	SP; M	Reduces time with fewer manufacture processes and simplified jointing	①; ④
10	Use as environmentally friendly materials as possible		Reduces harm to the environment and residents	③
11	Minimize the part count	SP	Reduces time and costs with simplified design, manufacture, and assembly	①; ②; ③; ④
12	Minimize and standardise connector types and quantity	SP; SD	Reduces time and costs with simplified design, manufacture, assembly, repair and maintenance	①; ②; ③; ④
13	Minimize the use of fragile parts	SP	Reduces costs due to fewer part failures, and easier handling and assembly	①; ④
14	Do not over-specify tolerances or surface finish	F; SP	Reduces time and costs with easier manufacture	①; ④

217 Note: A=Automation; F=Flexibility; M=Modularity; SD=Standardization; SP=Simplification.  
 218 ①=Bogue, 2012; ②=Stoll, 1986; ③=Emmatty and Sarmah, 2012; ④=Swift and Brown, 2013

219

### 220 *Similarities and differences between manufacturing and construction*

221 Transplanting DfMA guidelines from manufacturing to construction first requires  
 222 understanding the connections and distinctions between the two industries. Manufacturing can  
 223 be defined as “the process of transforming materials and information into goods for the  
 224 satisfaction of human needs” (Chryssolouris, 2013). It is often linked to the concept of “mass

225 production”, evolving to successfully adopt machinery and information technologies to achieve  
226 cost-effective production (Lanigan, 1992; Crowley, 1998). Construction can also be considered  
227 as production process with products that are location-based and involve heavier onsite assembly,  
228 e.g., buildings, bridges, roadways, and other infrastructure (Jewell et al., 2014). It is a project-  
229 based activity employing huge human, material, and machine resources and involving heavy  
230 investment (Chitkara, 1998).

231  
232 Manufacturing and construction share many managerial practices, however. For example, they  
233 both engage multiple stakeholders to participate in the design, procurement, production, and  
234 logistics and supply chain management (LSCM) process (Winch, 2003). The process of  
235 producing physical products can be intensive, and thus requires skilled labor and a high level  
236 of technology (Sanvido et al., 1990). In recent years, as construction shifts towards  
237 prefabrication and other manufacturing techniques, the distinctions between these two  
238 industries have blurred. Some scholars advocate construction as a manufacturing process,  
239 intending to encourage adoption of manufacturing processes and guidelines (e.g., Crowley,  
240 1998; Gann, 1996). The underpinning idea is to make the construction process more  
241 controllable to alleviate the long-lasting problems of the industry such as low efficiency, poor  
242 quality control, and labor shortage.

243  
244 Still, construction differs from manufacturing in its end products and production process.  
245 Construction outputs are generally more sophisticated (Sanvido et al., 1990). Unlike  
246 manufacturing goods produced at factories and transported to end users, construction outputs  
247 are largely built in place (Paez et al., 2005). The unique features of construction outputs lead to  
248 the more dynamic, highly localized, and complex nature of construction process. For example,  
249 construction involves an onsite production cycle that could last for years and many  
250 contingencies and risks can occur during this period (Koskela, 1992; Paez et al., 2005). It is  
251 challenging for proactive planning, visual control, and orderly management (Aapaoja and  
252 Haapasalo, 2014). Compared to manufacturing with its relatively standardized workflow,  
253 construction is a highly localized activity that involves using locally available resources and  
254 taking into account local geographic, economic, social and climatic constraints (Akanni, et al.,  
255 2015). The site-specific, one-of-a-kind nature of construction projects makes it difficult to apply  
256 a standardized routine that has been proved efficient by other projects (Koskela, 1992; Jewell  
257 et al., 2014; Aapaoja and Haapasalo, 2014).

258  
259 Even though offsite construction is quite similar to manufacturing and hence presents an  
260 unprecedented opportunity for DfMA, they are not the same. Some major components can be  
261 manufactured, e.g., in an offsite precast yard, but a considerable portion of the construction and  
262 assembly work are still conducted onsite. Full modular integrated construction has never been  
263 the ultimate choice (Lu et al., 2018). Construction LSCM of raw materials and precast  
264 components play a key role in the success or failure of prefabrication construction (Zhong et



265 al., 2017). The final products are still location-based, confined by site conditions and bespoke  
 266 requirements from diverse clients. As shown in Table 2, the differences mentioned above are  
 267 summarized into six perspectives, including place, power, mode, form, period, and process. All  
 268 these features together necessitate a closer look at “general” manufacturing DfMA guidelines  
 269 to propose a set of guidelines that are more construction-oriented.

270

271 **Table 2.** Difference between manufacture industry and construction industry

<b>Perspectives</b>	<b>Manufacture industry</b>	<b>Construction industry</b>
Place	Lowly localized activity	Highly localized activity
Power	Factory mechanization	Labor-intensive onsite
Mode	Mass production	Customized design
Form	Product-based activity	Project-based activity
Period	Short cycle	Long cycle
Process	Standardized workflow	Non-standardized workflow

272

273 ***Tentative DfMA guidelines for construction***

274 Several studies have tried to apply DfMA in construction, as shown in Table 3. Most of these  
 275 guidelines directly adopted the manufacturing-oriented DfMA (see Table 1) or made some  
 276 adaption, mainly by changing their descriptions . Gbadamosi et al. (2019) generalized the four-  
 277 category of guidelines by considering DfMA and lean construction and developed a DfMA-  
 278 based optimizer for improving constructability. Kim et al. (2016) employed DfMA to overcome  
 279 the limitations of current bridge construction practice and to realize the standardization of  
 280 bridge construction in the UK. Chen and Lu (2018) reported DfMA guidelines for curtain wall  
 281 system specifically. Banks et al. (2018) introduced DfMA to support high-rise residential  
 282 construction. Safaa et al. (2019) proposed DfMA-based evaluation criteria for the prefabricated  
 283 bridge.

284

285 However, these studies do not adequately discuss the DfMA guidelines applied. Meanwhile,  
 286 some of the stated guidelines are inconsistent with current architectural and engineering design  
 287 practices. Hence, they cannot represent the core ideas of DfMA, such as improving  
 288 manufacturability and assemblability without reducing flexibility and functionality. Many  
 289 DfMA guidelines only consider reducing cost and number of components, not maintaining and  
 290 balancing other building attributes, and therefore cannot be used directly. More seriously, these  
 291 guidelines may make sense when being implemented individually, but can be easily  
 292 contradictory to each other if being applied together. Therefore, more systematic and iterated  
 293 guidelines need to be developed.

294

295 Considering context specificity and technical limitations, this study treats DfMA  
 296 implementation as a multi-criteria decision-making (MCDM) issue in the evaluation and  
 297 optimization of manufacturability and assemblability. Through systematical consideration,

298 these guidelines can be assigned importance weights during project process to achieve overall  
 299 optimization. Therefore, this research derive the five construction-oriented DfMA guidelines  
 300 shown in Table 4. The generalization of these guidelines is grounded based on the combined  
 301 consideration between existing DfMA guidelines and construction characteristics. Most of the  
 302 guidelines mentioned in Table 3 are summarized into component-integrated design which is  
 303 more closed to manufacture-oriented DfMA. Part of the guidelines are summarized into  
 304 material-lightened design, logistics-optimized design, and technology-rationalized design. In  
 305 addition, the inherent differences between the construction and manufacturing industries lead  
 306 to a new DfMA guideline – context-based design – for construction because the construction is  
 307 generally a highly localized activity (Akanni et al., 2015). Detailed descriptions of these five  
 308 guidelines are shown as follows.

309

310 **Table 3.** Some construction-related DfMA guidelines reported in the literature

311

	<b>Refer ence</b>	<b>Guidelines</b>	<b>Sources</b>
1	Gbad amosi et al., (2019 )	(1) ease of assembling parts	Minimize and standardise connector types and quantity (①; ②; ③; ④); Use standard and off-the-shelf components (①; ②; ③; ④)
		(2) ease of handling parts	Design for simple part orientation and handling (①; ②; ④); Minimize the part count (①; ②; ③; ④)
		(3) speed of assembling the whole system	Design with a predetermined assembly technique in mind (①; ④)
		(4) waste produced during operation	Use as environmentally friendly materials as possible (③)
2	Kim et al., (2016 )	(1) simplification in design	Design for ease of fabrication (①; ②; ④); Design for simple part orientation and handling (①; ②; ④)
		(2) reduced number of parts	Minimize the part count (①; ②; ③; ④)
		(3) standardization of commonly used parts and materials	Minimize and standardise connector types and quantity (①; ②; ③; ④); Use as similar materials as possible (①; ④)
		(4) ease of orientation, handling and assembly of parts	Design for simple part orientation and handling (①; ②; ④)
3	Chen and Lu (2018 )	(1) reducing the part count of curtain wall system	Minimize the part count (①; ②; ③; ④)
		(2) reducing the numbers of unique fasteners necessary to assemble the curtain wall system on the construction site	Minimize and standardise connector types and quantity (①; ②; ③; ④)

		(3) using cost-effective materials	Use as similar materials as possible ((1); (4))
		(4) making sure that the size and weight of components is easy to handle	Design for simple part orientation and handling ((1); (2); (4))
		(5) reducing waste of materials	Use as environmentally friendly materials as possible ((3))
4	Bank et al. (2018)	(1) use of prefabricated elements and modules	Use standard and off-the-shelf components ((1); (2); (3); (4))
		(2) reducing the number of unique parts	Minimize and standardise connector types and quantity ((1); (2); (3); (4)); Minimize the part count ((1); (2); (3); (4))
		(3) removing labor-intensive construction activities from site	Consider design for mechanized or automated assembly ((1); (3); (4))
		(4) placing the prefabrication activities in a controlled factory environment	Consider design for mechanized or automated assembly ((1); (3); (4))
		(5) using a highly automated approach	Consider design for mechanized or automated assembly ((1); (3); (4))
		(6) reducing waste in the process overall	Use as environmentally friendly materials as possible ((3))
		(7) improving efficiency in site logistics and a reduction in overall vehicle movements transporting materials to and from site	N/A
		(8) lowering the number of parts	Minimize the part count ((1); (2); (3); (4))
		(9) reducing the proportion of work carried out in the relatively harsh site environment	Consider design for mechanized or automated assembly ((1); (3); (4))
5	Safaa et al., (2019)	(1) simplicity of design	Design for ease of fabrication ((1); (2); (4)); Design for simple part orientation and handling ((1); (2); (4))
		(2) number of components	Minimize the part count ((1); (2); (3); (4))
		(3) standardization on elements or material	Minimize and standardise connector types and quantity ((1); (2); (3); (4)); Use as similar materials as possible ((1); (4))
		(4) ease of handling	Design for simple part orientation and handling ((1); (2); (4))

312

313

314

**Table 4.** Construction-oriented DfMA guidelines proposed in this study

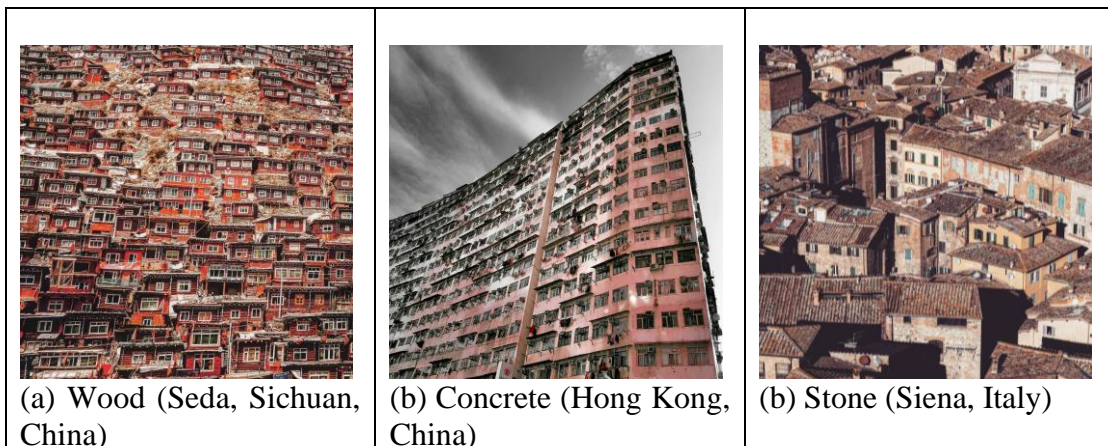
	<b>Guidelines</b>	<b>Perspectives</b>	<b>Generation sources</b>
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NO.			Existing guideline	Construction characteristics
1	Context-based design	Physical site		X
		Cultural locality		X
2	Technology-rationalized design	Onsite craftsmanship		X
		Off-site prefabrication	X	
3	Logistics-optimized design	Logistics inside the site		X
		Logistics outside the factory	X	
4	Component-integrated design	Finished surface	X	
		Connection joints	X	
5	Material-lightened design	Material properties	X	
		Structural system		X

315

316 *Context-based design*

317 For DfMA implementation in construction, context-based design is conducted from both  
318 physical site and cultural locality perspectives. Building process performance is highly  
319 influenced by context (McHarg, 1992; Kalay, 1999; Gifford, 2007), and manufacturability and  
320 assemblability are two important indicators of this performance. The physical, cultural, social,  
321 and other environments in which a building is embedded not only have an impact on the form  
322 of the building, but also on the building process. These factors provide references for the  
323 building design and process. As shown in Figure 2, different contexts cause different  
324 construction results. Seda, a traditional Chinese minority area, relies on mountains to build  
325 layers of wooden houses. High-density cities like Hong Kong utilize concrete for high-rise  
326 buildings. Old European towns, like Siena, build using bricks and stones. Based on the specific  
327 context, building practitioners can use localized craftsmanship, technology, and materials to  
328 tackle the difficulties in manufacturing and assembly process without compromising building  
329 quality and historical continuity. Thus, the context-based design method adapts the building  
330 process to the context to enhance manufacturability and assemblability.



(a) Wood (Seda, Sichuan, China)

(b) Concrete (Hong Kong, China)

(b) Stone (Siena, Italy)

331 **Fig. 2.** Context-based buildings (source: photo by authors)

332

333 *Technology-rationalized design*

334 Increase of manufacturability and assemblability does not have an absolute positive correlation  
335 with the depth of adoption of new technologies. Appropriate technology is seen as a more  
336 sensible approach than “rocket technology” in the construction industry (Ofori, 1994;  
337 Mitropoulos and Tatum, 1999; Lu, 2017). For example, Lu et al. (2018) recommended the  
338 implementation of an optimal rather than a high degree of prefabrication. Tan et al. (2019)  
339 highlighted the technology implementation barriers in different contexts and advocated  
340 appropriate technology implementation strategies. DfMA is considered an ideal way for  
341 prefabricated building production in many studies. Since it is not a case of “the higher the  
342 degree of prefabrication, the better”, the corresponding DfMA strategies must also change with  
343 the degree of prefabrication for better manufacturability and assemblability.

344

345 *Logistics-optimized design*

346 Optimizing construction logistics has a positive impact on the building process (Sobotka et al.,  
347 2005; Vidalakis et al., 2011; Lu et al., 2011). Compared with manufacturing production,  
348 building process, which involves off-site factories and onsite assembly, is complicated in terms  
349 of LSCM. Therefore, unlike Boothroyd (2005), architectural DfMA should not only consider  
350 the building product itself, but also LSCM. Banks et al. (2018) mentioned that DfMA needs to  
351 improve efficiency in site logistics and reduction in overall vehicle movements transporting  
352 materials to and from the site. It is necessary to consider the effectiveness of component  
353 transport and onsite placement on site when carrying out detailed design. Both logistics inside  
354 the site and outside the factory need to be considered interconnectedly.

355

356 *Component-integrated design*

357 The selection and combination of building components at the design stage is important to a  
358 construction project and requires knowledge of engineering, materials, and building equipment.  
359 Component-integrated design based on component characteristics and construction logic can  
360 improve manufacturability and assemblability. For example, Zhang et al. (2018) proposed a  
361 high-speed, integrated component design method for modular houses whereby large  
362 components are assembled at the site factory, and aloft work and complex assembly operations  
363 are moved to the construction ground. Halfawy and Froese (2007) proposed a component-based  
364 framework for project system integration. These measures of integration improve assembly  
365 efficiency and reduce dangerous aloft work, which greatly reduces onsite safety hazards while  
366 improving the efficiency of onsite construction equipment and tools.

367

368 *Material-lightened design*

369 Lightweight buildings first emerged to alleviate the problems of manufacturing overcapacity  
370 and lack of social housing after World War II. Therefore, from birth, the lightweight building

371 is a product highly related to industrialized production. The material-lightened design  
 372 represents the material and structural efficiency when creating the volume of space. It is also  
 373 the impact of the overall construction on the environment as little as possible. Both light timber  
 374 (Scotta et al., 2015) and light steel (Jackson, 2016) have been appraised for rapidity of  
 375 realization, affordability, and flexibility in design and construction. Chen and Lu (2018) also  
 376 highlighted the importance of easy-to-handle size and weight of components in DfMA.  
 377 Reduction in overall building weight helps to improve efficiency in activities related to  
 378 manufacturing and assembly. Production, transportation, and onsite manual work become more  
 379 convenient, as does subsequent demolition and relocation of the building. Under the material-  
 380 lightened design guideline, architectural design must consider not only the properties of the  
 381 material but also the weight reduction and achievement of the ideal stiffness-to-weight ratios.  
 382 It is also necessary to consider the structural system design of the building to achieve overall  
 383 weight optimization at the system level.

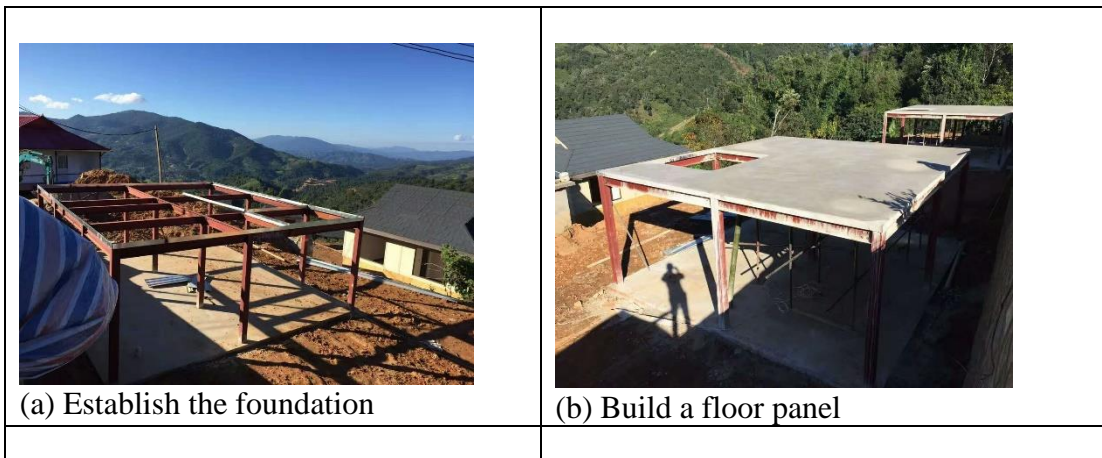
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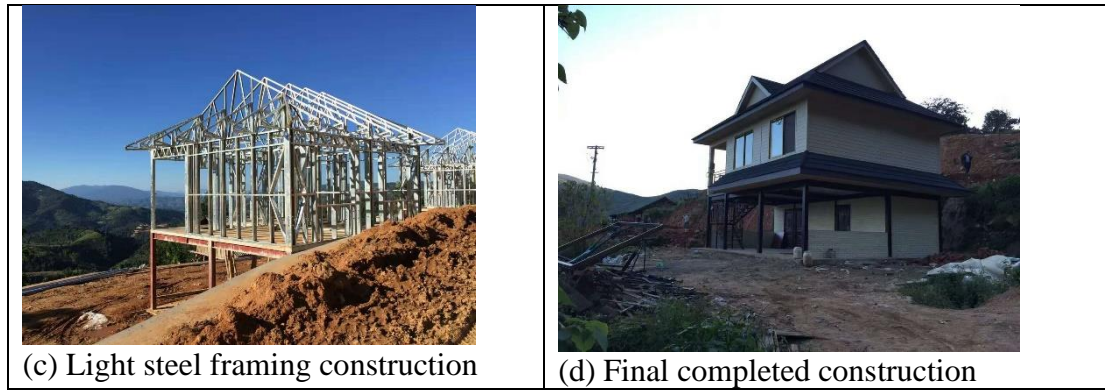
385 **A case study of a construction project pioneering DfMA-oriented design**

386 The selected case is a housing project located in Yunnan Province, China. It adopted a  
 387 prefabricated light steel-frame. The project was carried out by a real estate company under the  
 388 impetus of the Chinese government’s policy of *taking targeted measures to help people lift*  
 389 *themselves out of poverty*. The case is analysed in view of the five construction-oriented DfMA  
 390 guidelines as proposed by this study.

391

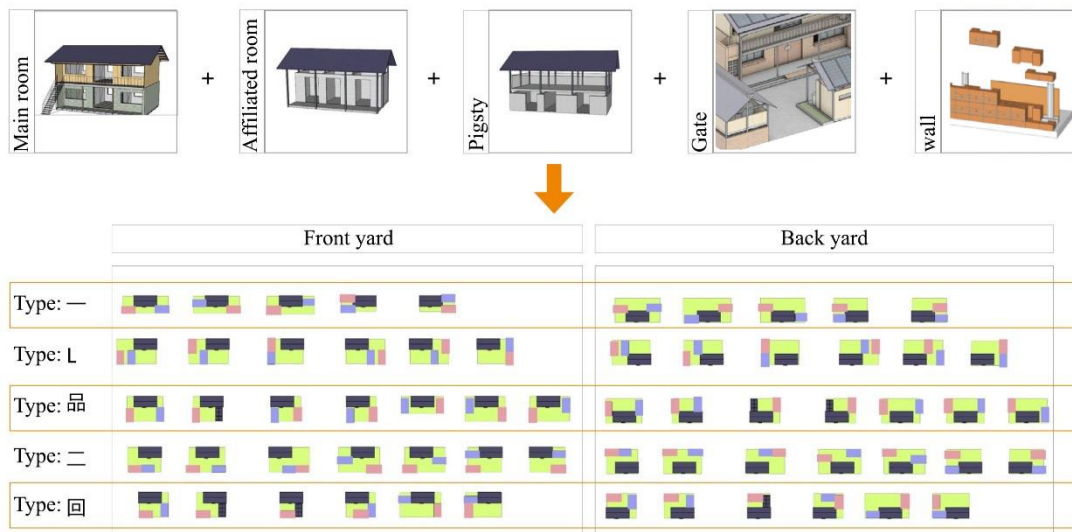
392 With regards to *context-based design* principle, the project adapted to the undulating terrain  
 393 through the underlying steel structural pillars while adopting ethnic minority *Dai*-style  
 394 architecture as seen in Figure 3. Figure 4 shows that topological deformation combinations,  
 395 planned courtyards, and entrance locations were organized into different residential space  
 396 modes according to different context conditions. Using context-based design principle, design  
 397 choices were more culturally and geographically adaptable and able to reflect local  
 398 characteristics.





399 **Fig. 3.** Building process (source: photo by authors)

400



401

402 **Fig. 4.** Design under the site context

403

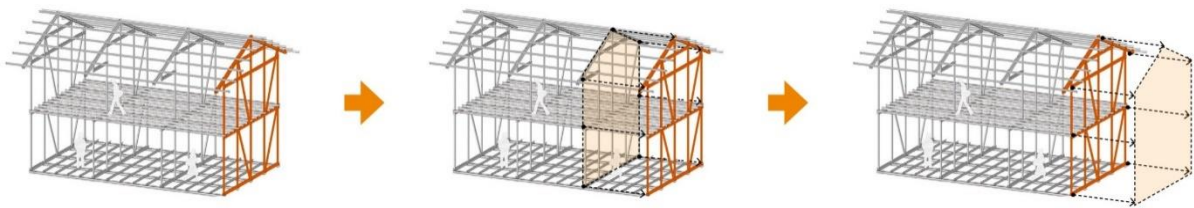
404 As for *material-lightened design* principle, this project is lightweight, of high strength and small  
 405 footprint, adopting a light steel-frame structure with high-efficiency lightweight thin-walled  
 406 profiles. The light steel framing system saves construction time and cost to a large extent. This  
 407 design highly responded to the integration of material properties and building structure system.  
 408 The structure is adaptable, the materials easy to recycle, and the project with low waste. Scotta  
 409 et al., (2015), Jackson (2016) and Chen and Lu (2018) all highlighted the importance of weight  
 410 in rapidity of realization. The lightweight steel-framed structure is likely to be close to zero  
 411 energy consumption in terms of energy and environmental performance of the building,  
 412 reducing waste during manufacturing and assembly (Roque and Santos, 2017; Santos and Silva,  
 413 2017). Due to factors such as environmental awareness and wood shortages, countries including  
 414 the U.S., Japan, the U.K, and Australia are actively promoting the application and development  
 415 of low- and medium-rise light steel structure houses.

416

417 In this project, the *component-integrated design* principle was consciously considered; the  
 418 production of components was automated, continuous, and highly precise. Product  
 419 specifications, especially connection joints and finished surface, were serialized, finalized, and

420 matched. It is easy to enlarge the column spacing and provide more separation space, which  
 421 can reduce the height and increase the building area (the saleable area can reach up to 92%).  
 422 Based on the component-integrated design, the advantages of adding floors, building renovation,  
 423 and building reinforcement are easily perceivable, as shown in Figure 5. Villagers decided the  
 424 size of the residential area to be built according to the actual situation of their own homes, and  
 425 they were able to reserve the land for later development. As shown in Figure 6, according to  
 426 their actual needs, the villagers could freely combine the components of the façade in the  
 427 available material library to form different effects and styles. These design strategies provided  
 428 flexibility and expandability for assembly based on component-integrated design.

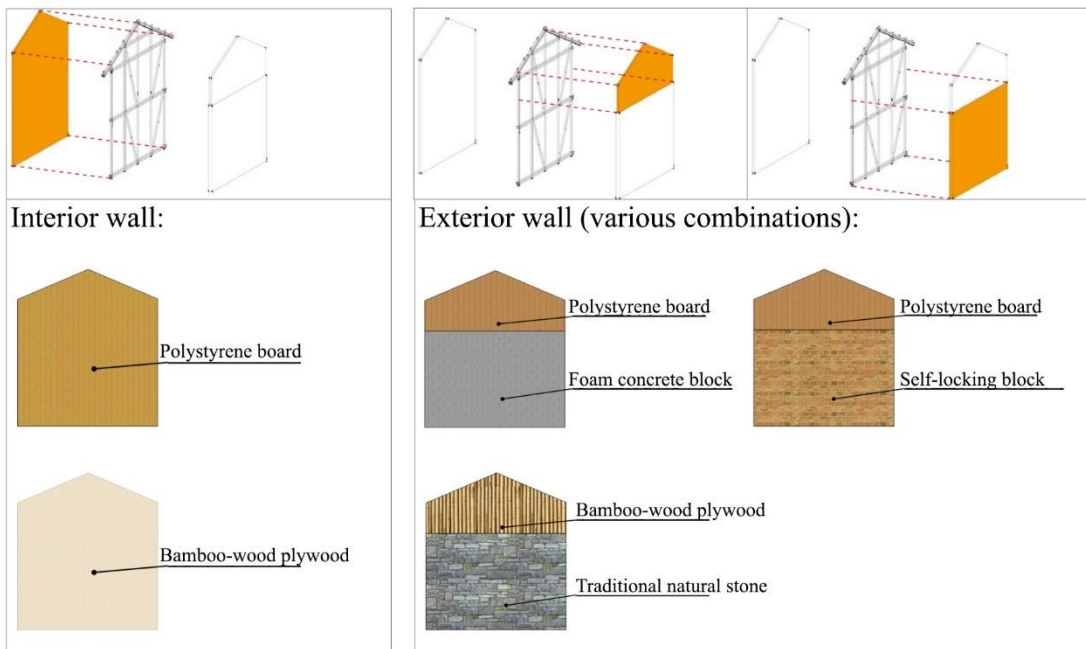
429



430

431 **Fig. 5.** Assembly expandability

432



433

434 **Fig. 6.** Facade material

435

436 This project also considered the *logistics-optimized design* principle in view of the difficulties  
 437 of logistics in the rural areas of Yunnan, where much of the terrain features tall mountains  
 438 without proper roads. The lightweight material reduced transport pressures and the design of  
 439 the components also took into account the size requirements of the transport. After the  
 440 prefabricated modules had been delivered to the site, the construction activities were carried  
 441 out immediately by the villagers, who learned and helped each other to complete the assembly

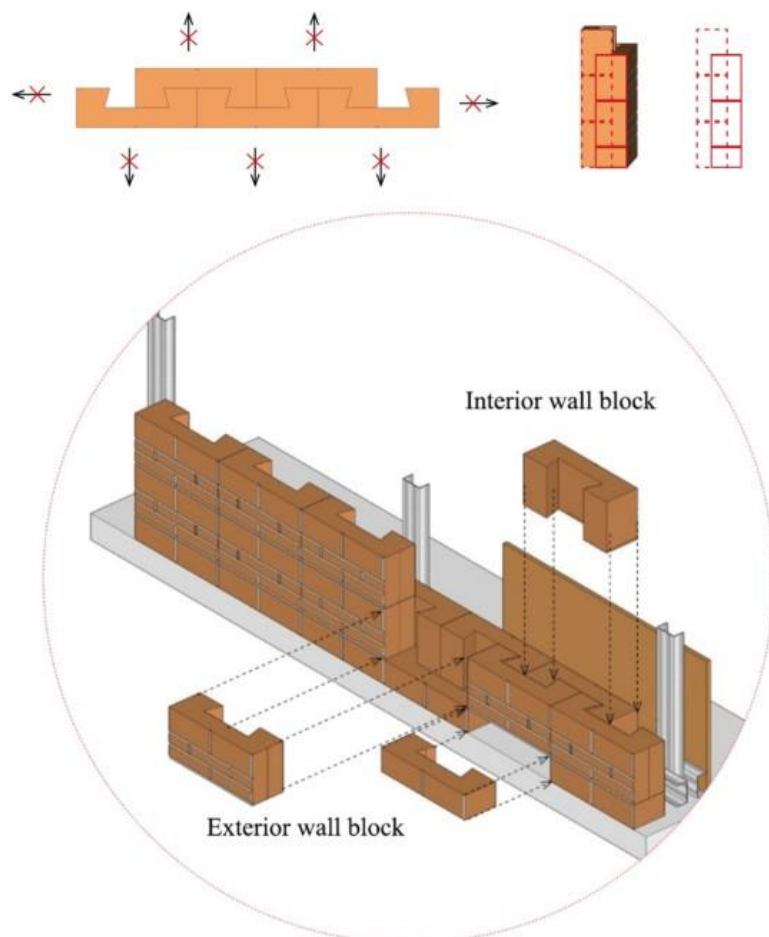


442 process of the houses. All dry works were carried out with little impact from the weather. A  
443 building of about 300m<sup>2</sup> required only five workers and 30 working days to construct.

444

445 For the *technology-rationalized* design principle, this project used low-tech but suitable  
446 technology to facilitate rapid construction by ordinary farmer workers and combined onsite  
447 craftsmanship and off-site prefabrication. For example, as shown in Figure 7, a new type of  
448 mortar-free and self-locking block was used. It can be recycled and used economically and  
449 environmentally. Unlike the traditional brick-concrete structure, the masonry can be bonded  
450 without relying on cement mortar. This saved labor costs and speeded up the building process.  
451 In addition, after the blocks were connected to the wall, the mechanical strength of the wall was  
452 increased, which can effectively mitigate the damage caused by earthquakes, typhoons,  
453 humidity, and floods.

454



455

456 **Fig. 7.** Brick wall construction method

457

### 458 **Discussion**

459 Traditional DfMA guidelines were developed from a manufacturing perspective. Although they  
460 make sense in some situations, architects complain that the guidelines ignore other critical  
461 elements such as site conditions, cultural context, flexibility of building forms, and LSCM.  
462 Some architects believe that architecture should not be just an industrial product, but rather an

463 organic product of the urban environment. Based on these conflicting opinions, the use of  
464 context-based design is proposed as a fundamental DfMA guideline. When implementing it,  
465 designers should pay attention to both physical and cultural issues related to the site, and try to  
466 make use of these characteristics for manufacturing and assembly.

467

468 In addition to interdisciplinary integration from manufacturing to construction, the adoption of  
469 technology is seen as an important factor affecting manufacturing and assembly. Technology  
470 can transform transportation methods, module components, and material processing. Thus, the  
471 second guideline is regarded as an enabler for DfMA implementation. The specific context  
472 determines the background, obstacles, results, and effects of technology implementation. In  
473 addition, various places, especially remote areas, may retain their own unique construction  
474 craftsmanship. Some forms of buildings, for example, have high requirements for onsite  
475 craftsmanship. Therefore, appropriate degree of prefabrication should be set for achieving  
476 optimal manufacturability and assemblability.

477

478 Optimization of the logistics is often overlooked at the design stage because architects often  
479 consider a building as a static product, rarely treating it as a building process. For architects to  
480 consider logistics, they need knowledge of project management and LSCM. This requires the  
481 architect to be more than just a designer, but also a coordinator of different types of work and  
482 a project manager to guide the building process. When it is impossible for an architect to possess  
483 all the knowledge of logistics, it is recommended to get construction or facility managers  
484 involved early in the design phase to perform, e.g. a buildability check, or pre-occupancy  
485 evaluation.

486

487 Component-integrated design and material-lightened design are also set as the construction-  
488 oriented guidelines. The prefabrication degree of each project may be different, resulting in  
489 different proportions of prefabricated components vs. cast in-situ. These two guidelines  
490 emphasize the integrated design of components and the lightweight design of materials. For the  
491 former, this study proposes to guide the production of components based on the finished surface  
492 of the building and to focus on the design of connection joints. The design from the finished  
493 surface to the detail can help the manufactured product to be closer to the final assembly  
494 requirements. Standardization of connection joints also increases the efficiency of  
495 manufacturing and assembly. For the latter, this study argues that reducing the weight of the  
496 material as much as possible will help DfMA implementation, as also evident in Gerth et al.  
497 (2013), Chen and Lu (2018), Roque and Santos (2017), and Santos and da Silva (2017).  
498 Utilizing the properties of materials means maximizing the use of physical properties and  
499 minimizing material modifications. These measures reduce the level of demand for total  
500 processing time. The emphasis on structural system design is to break down the limitations of  
501 single material consideration. From the whole system, it reduces the consumption required to  
502 process materials, thereby increasing manufacturability and assemblability.

503

504 It worth noting that these five guidelines may not have equal weight in every construction  
505 project. Due to the uniqueness of each project, it is necessary to change the importance of these  
506 guidelines in actual practice. For example, in remote areas, logistics-optimized design would  
507 weight higher than other four guidelines. Likewise, prefabrication and cast in-situ will also have  
508 different importance weights under different circumstances. Therefore, when implementing the  
509 DfMA guidelines proposed in this study, one should evaluate their weights rather than treating  
510 them equally each time. By doing so, with due respect to creativity and imagination in design,  
511 DfMA inevitably involves an iteration of MCDM that can be assisted by techniques such as  
512 Weighted Sum Method, Analytic Hierarchy Process, and Technique for Ordered Preference  
513 (Singh and Malik, 2014).

514

### 515 **Conclusion**

516 DfMA is both a design philosophy and methodology with a long history in the manufacturing  
517 industry. It has many advocates in the construction industry, who believe that DfMA can  
518 alleviate longstanding problems such as lackluster productivity, time delay, cost overrun, and  
519 poor safety. While there are considerable differences between manufacturing and construction  
520 in terms of production processes and final products, the resurgence of offsite prefabrication  
521 construction provides an unprecedented opportunity to adapt DfMA to construction.

522

523 Based on a critical investigation of existing DfMA guidelines and the similarities and  
524 differences between manufacturing and construction, we propose five construction-oriented  
525 DfMA guidelines. First, DfMA must consider context-based design because a construction  
526 project must attach to a land within a physical, natural, and cultural context. Second, building  
527 technologies provide unlimited options for construction but their availability and efficiency  
528 must be considered under a DfMA technology-rationalized guiding principle. Third, DfMA in  
529 manufacturing considers parts carefully but rarely their LSCM. In contrast, LSCM play a  
530 pivotal role in construction for both cast in-situ and offsite prefabrication construction.  
531 Therefore, DfMA in construction must consider the logistics-optimized design principle. Fourth,  
532 different levels of onsite and offsite distribution, and different levels of individual and  
533 integrated parts are major considerations in conducting a construction project. Therefore,  
534 DfMA must consider component-integrated designs. Fifth, materials are related to all the above  
535 guiding principles. Use of lightweight materials while guaranteeing structural efficiency is  
536 captured by the principle that DfMA must consider material-lightened designs.

537

538 The case study conducted in this study illustrated that the guidelines proposed in this study are  
539 rooted in the general DfMA guidelines but considers the heterogeneity of construction. It can  
540 be further decomposed into more detailed, operable sub-guidelines. Apparently, these  
541 construction-oriented DfMA guidelines can operate individually or collectively. The research  
542 helps to deepen the application of this new design philosophy in the construction industry

543 through proposing five more construction-oriented guidelines. In practice, these guidelines  
544 provide direct design guidance to designers, which in turn can lead to significant improvements  
545 in manufacturability and assemblability.

546

547 The guidelines proposed in this study are not exhaustive. Future studies are recommended to  
548 develop other architecture and construction-oriented DfMA guidelines and practices, with a  
549 view to improving design and construction. Some areas are particularly critical for such  
550 research efforts, e.g., (1) DfMA guidelines for onsite fabrication and prefabrication; (2) DfMA  
551 guidelines for different roles, such as project managers and designers; and (3) a  
552 standard/method for selecting guidelines, and measuring the degree of implementation and its  
553 improvement of manufacturability and assemblability.

554

### 555 **Data Availability Statement**

556 Some or all data, models, or code that support the findings of this study are available from the  
557 corresponding author upon reasonable request.

558

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