

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
22

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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., 2019). 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).

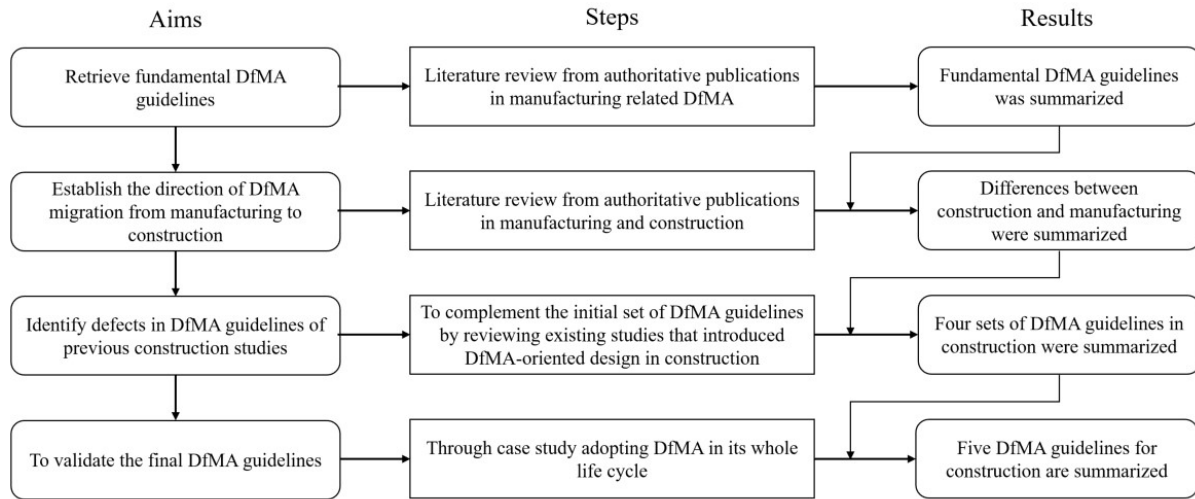
174

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., 2018b). 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

Perspectives	Manufacture industry	Construction industry
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

	Refer ence	Guidelines	Sources
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., (2018)	(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)

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

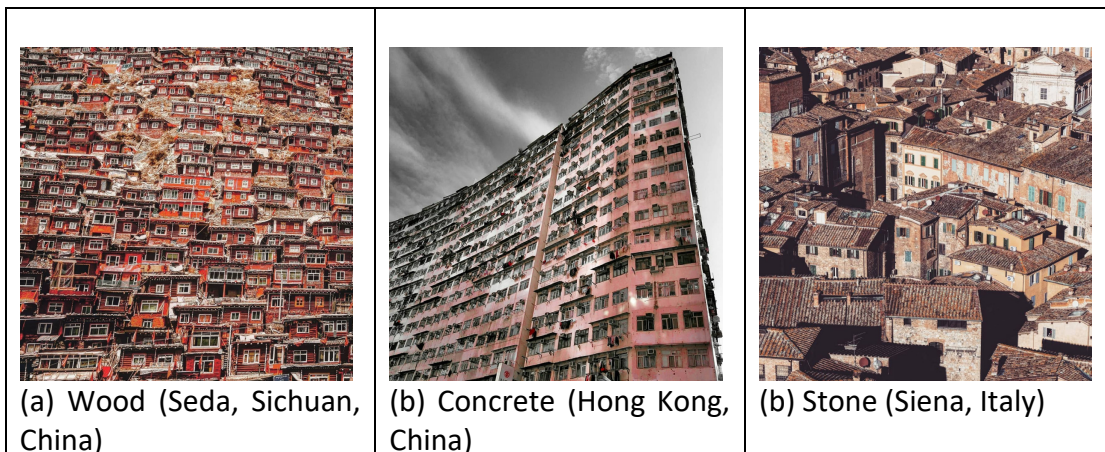
	Guidelines	Perspectives	Generation sources
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NO.			Existing guideline s	Construction characteristi cs
1	Context-based design	Physical site		X
		Cultural locality		X
2	Technology-rationalized design	Onsite craftsmanship		X
		Off-site prefabrication	X	
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.



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. (2018b) 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 (Flager et al., 2009) and requires knowledge of engineering, materials, and
359 building equipment. Component-integrated design based on component characteristics and
360 construction logic can improve manufacturability and assemblability. For example, Zhang et al.
361 (2018) proposed a high-speed, integrated component design method for modular houses
362 whereby large components are assembled at the site factory, and aloft work and complex
363 assembly operations are moved to the construction ground. Halfawy and Froese (2007)
364 proposed a component-based framework for project system integration. These measures of
365 integration improve assembly efficiency and reduce dangerous aloft work, which greatly
366 reduces onsite safety hazards while improving the efficiency of onsite construction equipment
367 and tools.

368

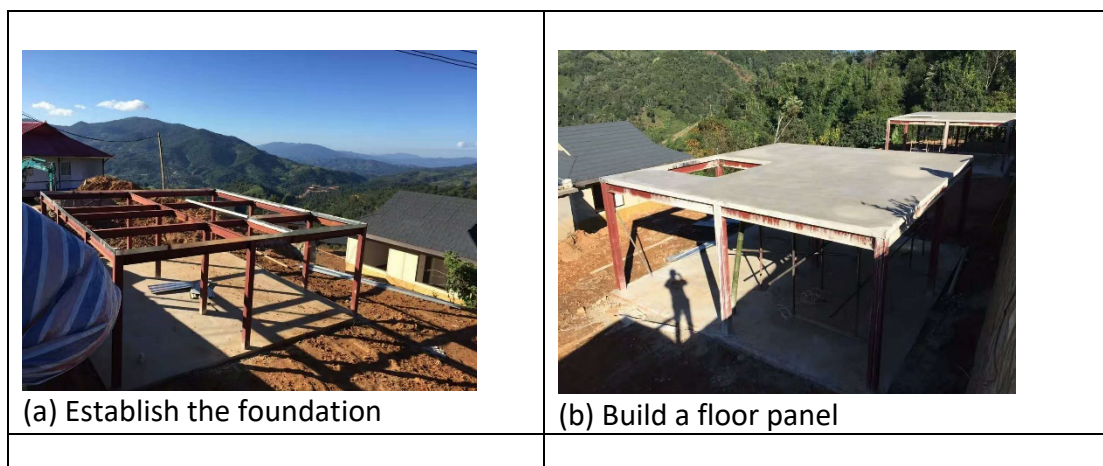
369 *Material-lightened design*

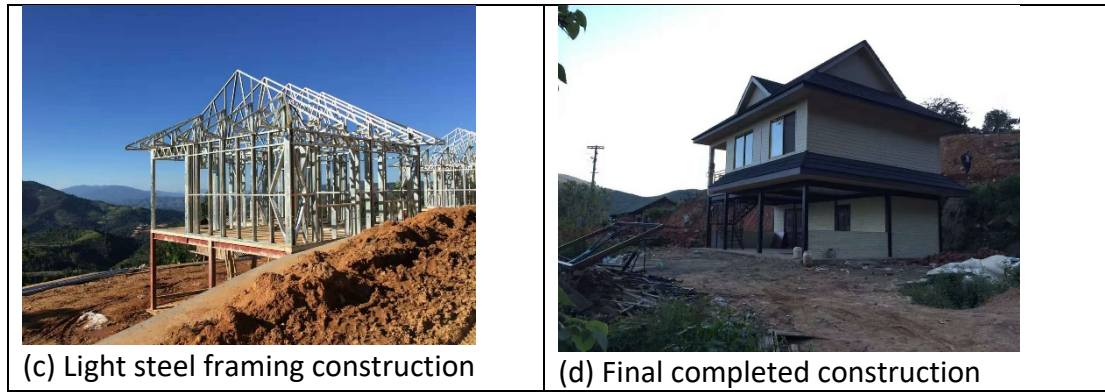
370 Lightweight buildings first emerged to alleviate the problems of manufacturing overcapacity
371 and lack of social housing after World War II. Therefore, from birth, the lightweight building
372 is a product highly related to industrialized production. The material-lightened design
373 represents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

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

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

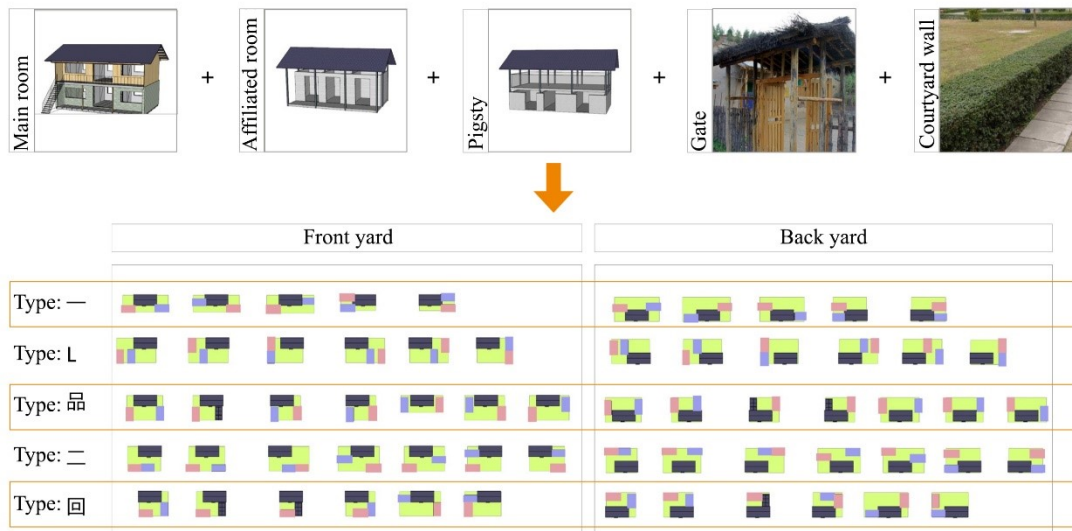
392
393 With regards to *context-based design* principle, the project adapted to the undulating terrain
394 through the underlying steel structural pillars while adopting ethnic minority *Dai*-style
395 architecture as seen in Figure 3. Figure 4 shows that topological deformation combinations,
396 planned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





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

401



402

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

404

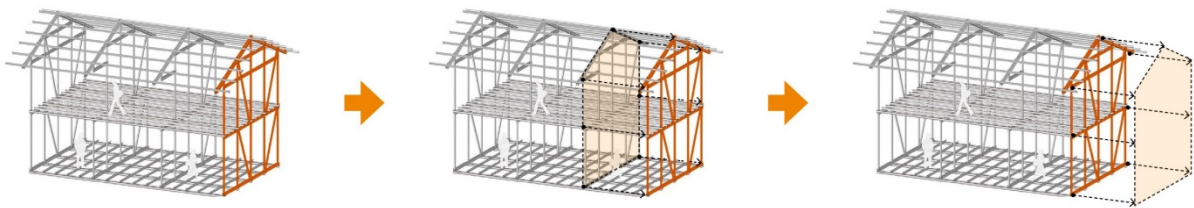
405 As for *material-lightened design* principle, this project is lightweight, of high strength and small
 406 footprint, adopting a light steel-frame structure with high-efficiency lightweight thin-walled
 407 profiles. The light steel framing system saves construction time and cost to a large extent.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

417

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

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

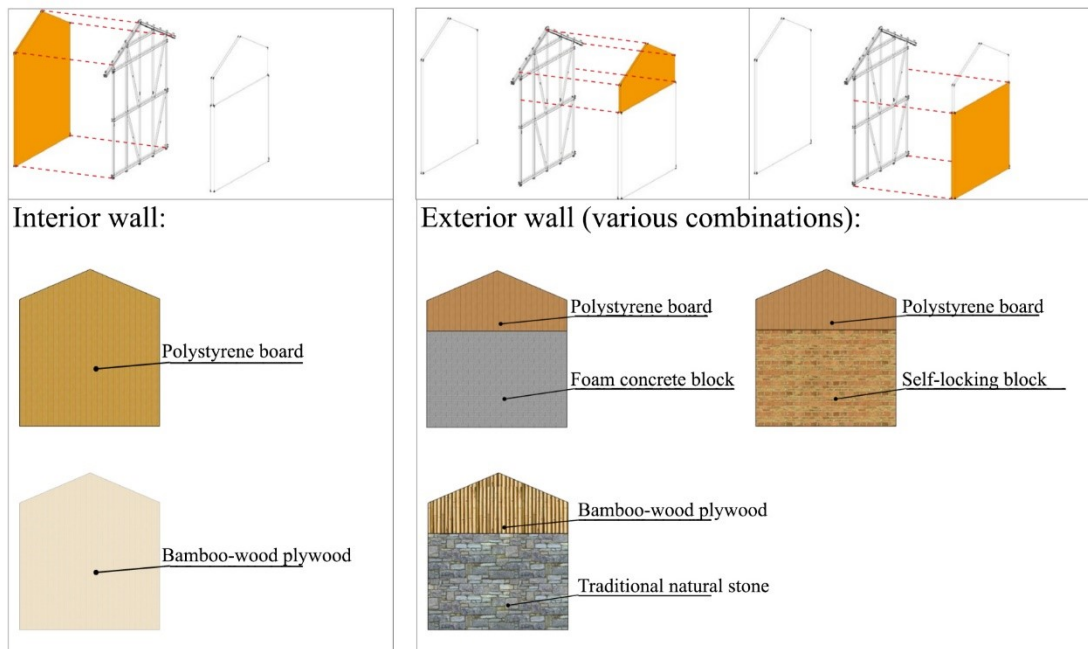
430



431

432 **Fig. 5.** Assembly expandability

433



434

435 **Fig. 6.** Facade material

436

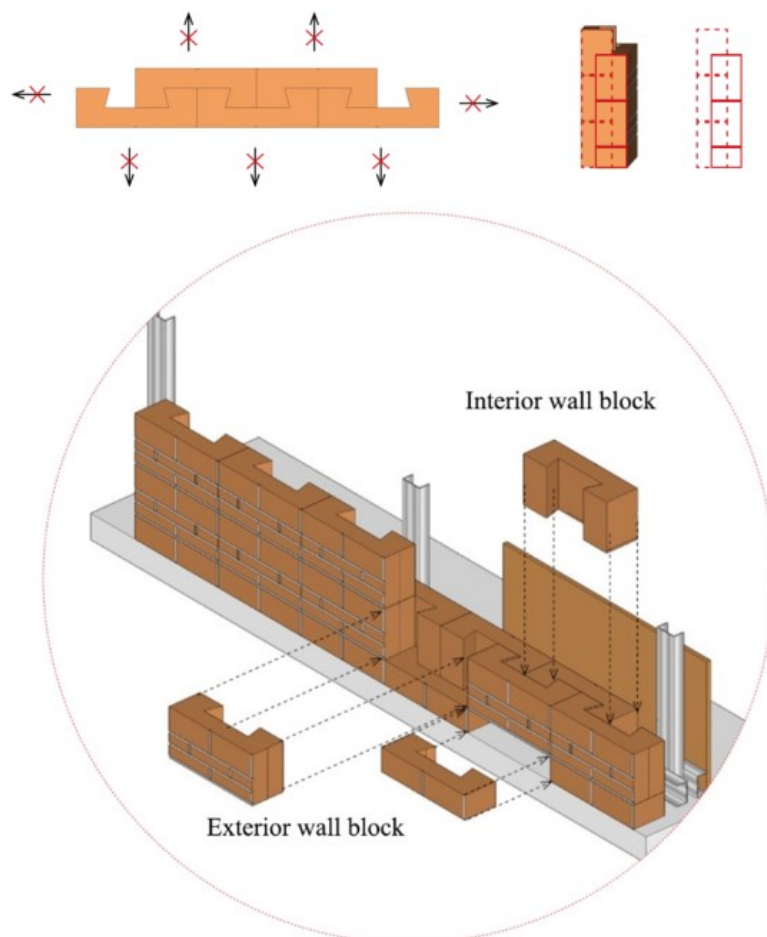
437 This project also considered the *logistics-optimized design* principle in view of the difficulties
 438 of logistics in the rural areas of Yunnan, where much of the terrain features tall mountains
 439 without proper roads. The lightweight material reduced transport pressures and the design of
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

443 process of the houses. All dry works were carried out with little impact from the weather. A
444 building of about 300m² required only five workers and 30 working days to construct.

445

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

455



456

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

458

459 **Discussion**

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

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

468

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

478

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

487

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

504

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

515

516 **Conclusion**

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

523

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

538

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

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

547

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

555

556 **Data Availability Statement**

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

559

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