

1 Offsite Construction: Developing a BIM-Based Optimizer for Assembly

2 ABSTRACT

3 The lack of adequate consideration of the underlying factors affecting the methods of building assembly
4 often results in inefficiencies in the uses of building materials, equipment and manpower. These
5 inefficiencies are further compounded by the nature of the construction industry, which traditionally
6 involves complex processes that result in wastages during production. To address this problem, this study
7 integrates the principles of Design for Manufacture and Assembly (DFMA) and Lean Construction to
8 develop a design assessment and optimization system to assist designers in the selection of alternative
9 building design elements and materials in a building information model. This assessment and optimization
10 system rely on metrics derived from production data associated with the ease of assembling, ease of
11 handling, the speed of assembling and the wastage during assembly or construction of a building element
12 or material. This paper presents the development of BIM-OfA assessment logic and its application for
13 assessment and optimal selection of building envelop through the extension of Building Information
14 Modelling (BIM). The system demonstrates its adequacy as an indicator of construction and material
15 efficiency, its integration with BIM further enhances the practicality of using production data such weight
16 of components, number of on-site workers and number of parts, for buildability assessment to improve
17 efficiency and reduce waste.

18 *Keywords: Assembly; Efficiency; DFMA; Lean Construction; Building*

19 1 INTRODUCTION

20 During the early stages of design conception, it is important to make guided decisions to enhance production
21 efficiency (Boothroyd, et al., 2004). Design for manufacture and assembly (DFMA) is a design procedure
22 and guideline that supports product simplification, integration of economic materials and processes into the
23 design with the goal of achieving optimal manufacturing and assembly (Boothroyd, et al., 2004). DFMA
24 has been successfully applied for various optimisation processes such as; enhancing early stage design
25 specification (Vliet & Luttermvelt, 2004), evaluating the ease of sourcing materials and manufacturing
26 components (Marion, et al., 2007), recommending manufacturing options for concurrent engineering to
27 designs (Howard & Lewis, 2003), developing assessment system for automatic assembly and developing
28 guidelines for designs for on-site assembly of building components (Lassl & Löfgren, 2006). Although the
29 manufacturing industry is far more efficient than the construction industry, there are some attempts to
30 optimize construction through design assessment for constructability (Zolfagharian & Irizarry, 2017).
31 Concepts such as standardization of parts, preassembly engineering, transportation, installation, and review
32 specification have been proposed to improve constructability of building designs (O'Connor, et al., 1987).
33 These concepts have a positive influence on improvement of construction efficiency, however, the overall

34 application of DFMA has more potential to significantly improve the design process for more efficient
35 fabrication and assembly of buildings (Yuan, et al., 2018). Furthermore, DFMA has a synergistic
36 relationship with the lean construction concept through the promotion of efficiency and waste reduction
37 especially in terms of the process of construction.

38 The application of lean principles in construction has great potential for design optimization and efficient
39 construction. Lean construction has been applied to optimize work schedules, manage the allocation of
40 materials and equipment to production just-in-time, and to plan congestion free work environment (Zhang,
41 et al., 2016). Despite the potential benefits of DFMA and lean construction, there is a lack of design
42 assessment tools that integrate both concepts to assist designers in appraising the implications of design on
43 efficient assembly. Construction processes can be continuously improved and standardized through the
44 concept of lean construction (Zhang, et al., 2016). Similarly, the adoption of principles from the concept of
45 DFMA can enhance the consideration of production knowledge at the design stages for the purposes of
46 optimization of design (Jürisoo & Staaf, 2007; BCA, 2016). With the current trend of digital technologies
47 in the construction sector, these concepts can be leveraged for continuous improvement (BCA, 2016;
48 Zhang, et al., 2016).

49 Data-driven technologies such as Building Information Modelling (BIM) has enhanced early-stage decision
50 making through advanced data visualization, clash detection, material quantity take-off and so on (Akinade,
51 et al., 2015; Mahamadu, et al., 2017). However, there remains no example of incorporation of production
52 economics data within BIM for the purposes of design appraisal or optimization (Zhang, et al., 2016). This
53 is due to the complexity of construction operations which results from the uniqueness of construction
54 processes, and the fragmentation within the industry which results in a wide variety of data formats
55 (Gbadamosi, et al., 2018). The applicability of BIM to various stages enables the use of information from
56 lean-based assembly principles such as DFMA for continuous improvement of design assessment and
57 optimization systems (Das & Kanchanapiboon, 2011; Akinade, et al., 2015; Tauriainen, et al., 2016). BIM
58 functionalities also present the opportunity to enhance the benefits of concepts such as; concurrent
59 engineering, just-in-time delivery, supply chain management, waste minimization, deconstructability and
60 reusability (Akinade, et al., 2015). Gbadamosi et al., (2018) affirmed that the adoption of successful
61 practices in the manufacturing industry such as DFMA and lean principles can improve the efficiency in
62 the construction industry. An extension of early-stage design capabilities to include principles of DFMA
63 and lean construction will enhance the overall efficiency of the construction industry through the
64 consideration of the critical factors that affect efficiency.

65 Based on the need to enhance design optimization through BIM, DFMA and lean construction, this study
66 aims to explore the relevant principles in order to develop a BIM-based optimizer (BIM-OfA) for assembly
67 of building design components. The following objectives have been addressed in this article.

68 (a) To identify factors for design assessment and optimization from DFMA and lean principles

69 (b) To develop an assessment logic of BIM-OfA for design optimization using the assessment
70 attributes derived from DFMA and lean principles

71 (c) To enable the use of digital data for the assessment metric through the integration of building
72 information model

73 The proposed framework resulted in indices which allowed appraisal of design options in relation to (i)
74 ease of assembly; (ii) ease of handling; (iii) waste greeted from the assembly; and (iv) Speed of assembly.
75 Based on these factors, a multi-criterion assessment metric was developed with factors priority weightings
76 developed based on Voting Analytical Hierarchy Process (VAHP) of construction experts. The assessment
77 metric is important to enhance the systematic consideration of DFMA and lean concepts at the early stage
78 of the building design. Furthermore, the assessment system will enhance the increased adoption of DFMA
79 and the use of BIM components for early-stage design with a view of the easy onsite assembly through lean
80 construction principles. The BIM-OfA assessment system will also enhance the efficient assessment of
81 building components for digital fabrication, efficient handling, and optimal on-site assembly.

82 **2 BUILDING DESIGN OPTIMISATION AND BIM**

83 The fundamental purpose of BIM adoption in building construction, design, and management (CDM)
84 process is to enhance optimization through effective communication, coordination, collaboration and
85 information management throughout the lifecycle (Grilo & Jardim-Gonvalves, 2010). At the early stage of
86 design, BIM can enhance various aspects of the CDM process such as waste minimisation (Akinade, et al.,
87 2015), supply chain assessment (Mahamadu, et al., 2017), whole-life performance estimation (Akanbi, et
88 al., 2018), off-site manufacturing (Abanda, et al., 2017) and so on. The capability of BIM to capture and
89 deliver quality information has enhanced the potentials of design optimization. However, the efficiency of
90 design optimization depends on the quality of information on which the design decisions are made
91 (Boothroyd, et al., 2004). In the manufacturing industry, concepts such as DFMA and lean manufacturing
92 have been used to improve production efficiency (Boothroyd, et al., 2004). Recently, the construction
93 industry has adopted concepts from the manufacturing industry to improve productivity (Aziz & Hafez,
94 2013). With the capability of BIM to capture and deliver information and the impacts of DFMA and lean
95 principles on design optimization in the manufacturing industry, it is imperative to consider the integration

96 of these concepts viz BIM, DFMA, and lean construction, for design optimization in the construction
 97 industry.

98 The essence of lean construction is waste elimination from the construction process and simplification of
 99 construction procedure and processes (Aziz & Hafez, 2013). In order to implement lean construction,
 100 reliable production data can be developed during construction operations and used for design decision
 101 making, where production characteristics of design elements and materials selected are considered in order
 102 to choose those that offer the cleanest approach to construction. Some examples of BIM use to support lean
 103 concepts includes detection of work sequence conflicts, analysis of workspace congestion, enhancement of
 104 on-site communication, improvement of material sourcing efficiency and development of efficient
 105 workflows (Mallasi, 2006; Aziz & Hafez, 2013). Since lean principles are beneficial for design
 106 optimization, there is an opportunity to align these principles with DFMA principles which are focused on
 107 early-stage consideration of the efficiency of manufacturing and assembly. Furthermore, the potentials of
 108 the integrated principles can be maximized through virtual prototyping with the aid of technologies such as
 109 BIM (BCA, 2016).

110 Table 1 shows the synergies and interrelationship between DFMA and lean construction based on their
 111 principal underlying concepts. Some principles of DFMA and lean construction have common optimisation
 112 factors such as assembly duration and waste minimization. Although, some optimisation factors such as the
 113 types of assembly fasteners and secondary finishes are only considered within DFMA principles. However,
 114 these optimisation factors contribute to some other principles of lean construction such as waste
 115 minimisation. Furthermore, the principles of DFMA and lean construction and complementary on many
 116 aspects and can be combined to improve the overall efficiency of construction.

117 **Table 1:** The relevant assembly optimisation factors from DFMA and Lean construction concepts

Concepts		Geometric complexity	Parts Standardization	Quality of parts	Workforce/Expertise	Equipment required	Handling difficulty	Type of material	Type of fasteners	Secondary finishes	Number of parts	Size of parts	Weight of parts	Accessibility of joint	Waste minimization	Stability of parts	Workspace conflict	Sequence conflict	Assembly duration
<i>DFMA</i>	DFMA® (Boothroyd, et al., 2004)	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
	DFA- Bralla method (Bralla, 1999)	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
	DFA- Lucas method (Redford & Chal, 1994)	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
	DFA(OS)-On-site (Lassl & Löfgren, 2006)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
	DFA 2 (Rapp & von Axelson, 2003)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>
<i>LEAN</i>	LPS- Last planner system (Paez, et al., 2005)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
	Kanban System (Just-in-time) (Paez, et al., 2005)	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>

Concurrent Engineering (Aziz & Hafez, 2013)	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>
PCMAT-work environment (Aziz & Hafez, 2013)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
QMT- Quality management (Paez, et al., 2005)	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
Visual Inspection (Paez, et al., 2005)	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>	<input checked="" type="checkbox"/>	<input checked="" type="checkbox"/>	<input type="checkbox"/>

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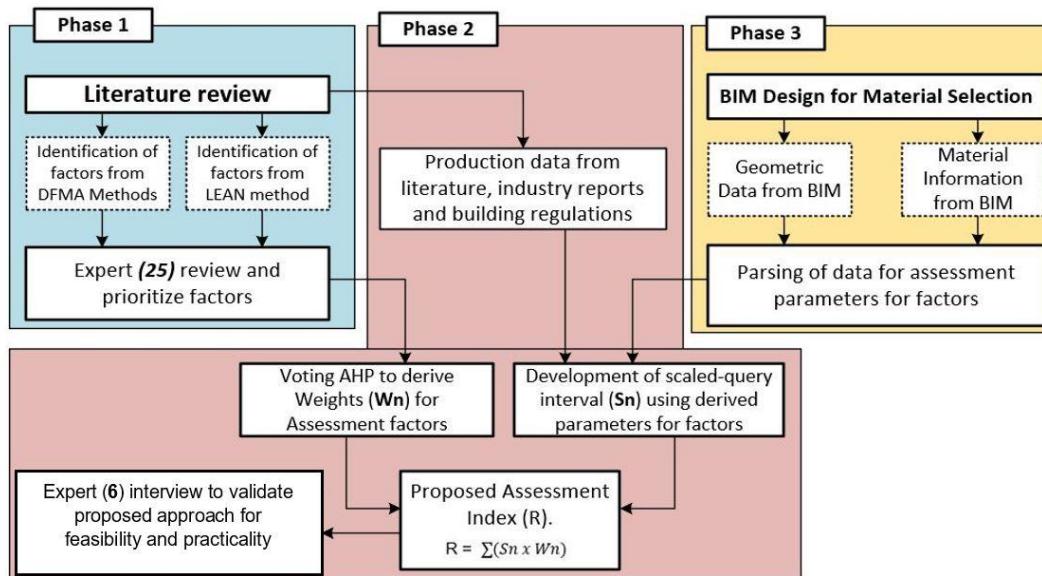
119 Although the concept of DFMA is yet to be embraced in the construction industry (BCA, 2016), assessment
 120 of design constructability is a common practice in construction planning. Some studies developed
 121 constructability evaluation models using the multi-objective approach due to the complex nature of
 122 construction (Lam, et al., 2007; Zhang, et al., 2016; Zolfagharian & Irizarry, 2017). Some constructability
 123 assessment criteria identified from these studies include standardization, part minimization, preassembly
 124 engineering, installation, and specifications review. (Kannan & Santhi, 2013) also used constructability
 125 assessment criteria such as sustainability, safety, and quality indexes. Although the focus of these attributes
 126 is mainly on traditional construction methods, the basis of constructability assessment is to enhance the
 127 consideration of the method of construction at during design (Lam, et al., 2007). The multi-objective
 128 approach to design assessment is very useful for integrating the concepts of DFMA and lean principles for
 129 design optimization for building assembly.

130 Despite the synergy and availability of metrics for assessing these concepts, no examples exist of their
 131 application in assessing building design, especially through BIM. The next section outlines the
 132 methodology adopted in this paper to achieve the development of a novel approach to assessing building
 133 design in relation to its contribution to efficient and lean construction based on DFMA assessment
 134 principles.

135 3 METHODOLOGY

136 The following recommendations were adopted in developing this assessment approach based on DFMA
 137 and lean principles for design optimisation through virtual prototyping: (i) Assessment models should
 138 enhance flexibility through user-based evaluation (Das & Kanchanapiboon, 2011). The user-based
 139 evaluation allows the flexible application of the system by various users for their unique projects. (ii)
 140 Assessment tools should be based on a multi-objective approach for scaled evaluation (Akinade, et al.,
 141 2015; JÜrisoo & Staaf, 2007; Das & Kanchanapiboon, 2011), because construction operations are complex,
 142 and many factors affect the efficiency, assessment tools should incorporate multiple objectives affecting
 143 construction. (iii) Assessment principles should be integrated as an additional knowledge base attached to
 144 parametric design authoring software such as BIM design tools to ensure applicability (Akinade, et al.,

145 2015; BCA, 2016). These recommendations were adopted because they will enhance the interoperability
 146 of the assessment system with BIM design tools and ensure the flexibility for users.



147

148 **Figure1:** Framework for developing BIM-OfA assessment metric

149 The implementation of the proposed framework entailed three phases. In the first phase, factors that are
 150 critical to the efficiency of assembly processes were identified from an in-depth review of the literature on
 151 the concepts of DFMA and lean construction. Table 1 shows the occurrence of these preliminary factors as
 152 identified from various methods and principles of DFMA and lean construction. A panel of experts in the
 153 construction industry reviewed and prioritized these factors using priority voting survey. The experts were
 154 defined based on their knowledge of BIM, offsite construction, lean construction and DFMA, the focus of
 155 the expert survey was on the level of knowledge of the participants rather than the quantity of participants.
 156 Therefore, 40 experts were involved in the expert engagements. Phase-two of the study entailed the analysis
 157 of results from the priority voting to derive the weighted importance of each factor to the assessment of
 158 optimized assembly design. A scaled-query interval was also developed from literature, industry reports,
 159 building regulations and in consultation with the experts to enable the development of assessment metric.
 160 The scaled-query interval was reviewed by the experts during expert engagements and the outcome was
 161 revised and validated.

162 The assessment interval was developed on a scale of (0-5) from the literature review and expert discussions
 163 using quantitative and qualitative parameters that affect the efficiency of assembly processes. The third
 164 phase of the proposed framework was conducted in parallel with phase one. In the third phase of the
 165 framework in Figure 1, a case study model was designed to test the applicability of the assessment system

166 for alternative wall materials with BIM environment. The four materials considered for the application were
167 (a) *precast concrete*; (b) *brick*; (c) *prefabricated exterior insulation finish systems (EIFS) on a metal frame*
168 and; (d) *concrete blockwork*.

169 **3.1 Identification of Assessment Criteria**

170 As shown in Table 1, five methods of DFMA concept were integrated with six lean techniques were used
171 for the identification of important factors for design optimization for assembly. Aside from the pioneering
172 concept of design for manufacture and assembly (DFMA) according to Boothroyd, four other methods of
173 DFMA concept were used. These methods include: (a) Design for assembly (DFA) according to Bralla
174 (1999): This method has similar guidelines to DFMA; however, this method specifically focusses on design
175 simplification, part minimization and enhancing easy handling during assembly; (b) Design for assembly
176 (DFA) according to Lucas: This method mainly focusses on assemblability and assembly sequence
177 optimisation. It also includes a functional analysis of parts to identify opportunities for standardization
178 (Redford & Chal, 1994); (c) Design for assembly on-site (DFA-OS): The focus of this method is assembly
179 performance on site, it seeks to minimize the reliance of the assembly process on large equipment,
180 temporary structures and mobile equipment on-site (Lassl & Löfgren, 2006); (d) Design for assembly 2
181 (DFA2): This method was developed for automatic assembly by IVF (Rapp & von Axelson, 2003).

182 On the other hand, the six techniques of lean construction that were considered are: (a) Last planner
183 system (LPS): The focus of this technique is to optimize assembly through assessment of workflow,
184 production rate, assembly methods and assembly requirements for each production unit. This assessment is
185 done collaboratively by a group of leaders from various production units and the manager (Paez, et al.,
186 2005); (b) The Kanban system: This technique is based on the just-in-time principle, it is used to manage
187 the allocation of materials and tools for various assembly (Paez, et al., 2005); (c) Concurrent engineering:
188 This method is used to improve assembly schedule and sequence efficiency by overlapping activities,
189 splitting activities and improving transition time between activities (Aziz & Hafez, 2013); (d) Plan
190 conditions and work environment (PCMAT): This technique helps to ensure proper layout of assembly site
191 to avoid congestion, workspace conflict and enhance safety (Aziz & Hafez, 2013); (e) Quality management
192 tools: The essence of this method is to ensure that quality management tools are integrated into lean
193 construction to enhance the quality of parts, connectors, tools, and work. It often involves a point system
194 of evaluating quality controls (Paez, et al., 2005); (f) Visual Inspection: This method of lean construction
195 is used for managing materials, components, activities, and information through visual prototyping tools.
196 The purpose of this method is aligned with the capabilities of BIM (Paez, et al., 2005).

197 The following guidelines were identified to be applicable in developing an assessment system from the
198 DFMA and lean methods discussed: (i) Fasteners and joints should be durable, reusable and

199 multifunctional. Preference should be given to non-permanent joints such as bolts & nuts and the processing
 200 or wet operation of assembly joints on-site should be minimized or eliminated; (ii) Designer should limit
 201 the use of materials that require secondary finishes on-site for aesthetics, durability or fire protection. It is
 202 preferable for all components to arrive onsite without further processing required aside from assembly and
 203 fastening; (iii) Designer should make use of opportunity to standardize parts and components to enhance
 204 mass production and repeatability; (iv) Parts with composite materials should be avoided and material
 205 variation in general design should be limited to enhance smooth workflow; (v) Regular and symmetrical
 206 shape with adequate tolerance is desirable for parts and component design to enhance easy assembly; (vi)
 207 The number of building parts should be minimized as much as possible to allow for easy storage onsite and
 208 easy delivery to production units;

209 **Table 2: Categories of Identified assessment Factors**

210

Categories	Factors	References
Ease of assembling parts	Connection between parts	(Akinade, et al., 2015; Crowther, 2005; Webster & Costello, 2005; Guy, et al., 2006)
	Connection to main building elements	(Akinade, et al., 2015; JÜrisoo & Staaf, 2007; Crowther, 2005; Webster & Costello, 2005; Guy, et al., 2006)
	Post-assembly secondary finishes	(Akinade, et al., 2015; JÜrisoo & Staaf, 2007; Crowther, 2005; Webster & Costello, 2005; Guy, et al., 2006)
	Standardization of parts	(JÜrisoo & Staaf, 2007; Crowther, 2005; Webster & Costello, 2005; Guy, et al., 2006)
	Multiple material usage in production	(Akinade, et al., 2015; Crowther, 2005; Webster & Costello, 2005; Guy, et al., 2006)
	Geometric complexity of parts	(Akinade, et al., 2015; Crowther, 2005; Webster & Costello, 2005; Guy, et al., 2006)
Ease of handling parts	Number of parts	(Boothroyd, et al., 2004, Akinade, et al., 2015; JÜrisoo & Staaf, 2007, BCA, 2016; Webster & Costello, 2005, Guy, et al., 2006)
	Weight of parts	(Akinade, et al., 2015; JÜrisoo & Staaf, 2007; Guy, et al., 2006; Lassi & Löfgren, 2006)
	Tools and equipment requirement	(Lam, et al., 2007; Das & Kanchanapiboon, 2011)
	Fragility of parts	(Lassi & Löfgren, 2006; Rapp & von Axelson, 2003; Redford & Chal, 1994)
	Quality control requirement	(Tauriainen, et al., 2016; Das & Kanchanapiboon, 2011)
	Number of workers required	(Tauriainen, et al., 2016; Das & Kanchanapiboon, 2011)
Speed of assembling the whole system	Speed of assembly in relation to labor and equipment cost	(Tauriainen, et al., 2016; Crowther, 2005; Guy, et al., 2006; Chini & Bruening, 2003)
Waste produced during operations	Waste index of parts and applied finishes	(Akinade, et al., 2015; Tauriainen, et al., 2016; Crowther, 2005; Guy, et al., 2006; Chini & Bruening, 2003; Ekanayake & Ofori, 2004)

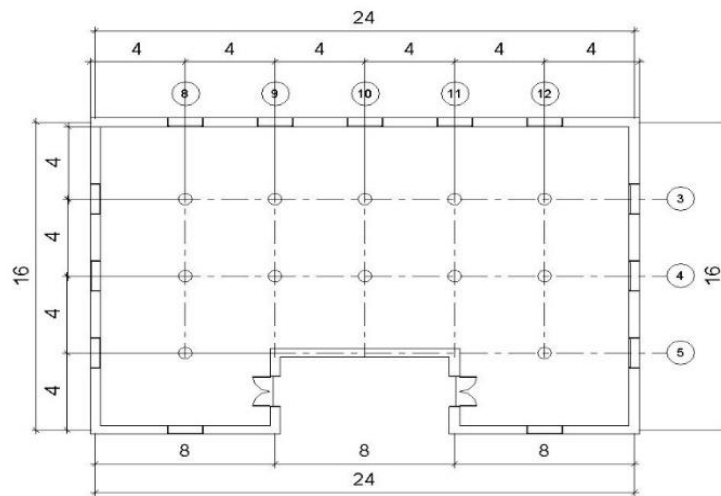
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212 (vii) The weight of parts should be within the efficient handling capacity of workers and machines to avoid
 213 fatigue, accident, damages and assembly errors. Therefore, the density of materials should be considered
 214 during design; (viii) Assembly operations that require the use of too many tools and equipment should be
 215 avoided, tools should be minimized, and multipurpose equipment is preferable; (ix) Fragile parts that
 216 require special damage protection and handling should be avoided, parts should be compact and not loose;
 217 (x) Complex parts that require expert quality assurance should be avoided unless necessary, design should
 218 enable easy quality control and less sampling; (xi) The number of assembly workers should be minimized

219 as much as possible through the design of efficient assembly system; (xii) The efficiency of the assembly
 220 process is determined by the amount of work done with available resources. Efficiency should be as high
 221 as possible to minimize resource used and maximize work done; (xiii) Assembly choices with minimum
 222 material waste are preferable. Important factors such as components and fastener standardization,
 223 minimization of on-site equipment and workforce, and so on were identified from the guidelines and
 224 principles. A consolidated list of assessment criteria was derived resulting in a list of 14 presented in Table
 225 2.

226 3.2 Design of Case Study

227 A BIM model was developed to demonstrate the practicality of design assessment for assembly. The
 228 plan is a simple commercial building, the layout floor has an area of 347m² and unconnected height of 3m.
 229 The perimeter of the building envelop is 88m and the area of the wall is 220m². Using these characteristics
 230 case study prototype, four building envelope materials were used to experiment the assessment approach,
 231 viz; (a) precast concrete; (b) brick; (c) prefabricated exterior insulation, finish systems (EIFS) on a metal
 232 frame and; (d) concrete blockwork



233
 234 **Figure 2:** Layout of the design case study (Dimension in meters)

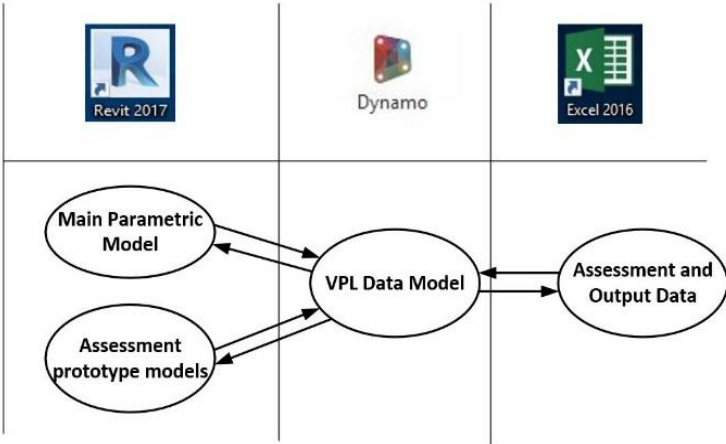
235 4 DEVELOPMENT OF BIM-BASED OPTIMIZER FOR ASSEMBLY (BIM-OfA)

236 The functionality of the assessment system relies on information exchange throughout the assessment
 237 and prototyping process. As a means of integrating the geometric and functional data of different material
 238 options within a BIM (Autodesk Revit) environment with computational data of assessment conditions
 239 stored in an external database (Microsoft Excel), visual programming language (VPL-Dynamo) is used to
 240 query basic information (i.e. material/element type and attributes such as geometry or quantities) from the
 241 Revit BIM model into the external database as demonstrated in Figure 4. The VPL tool selection was based

242 on its interoperable capability to create bi-directional information exchange with the assessment tool and
 243 main parametric modeling tool. Also, the VPL tool can develop visualized prototypes of design alternatives.
 244 For the experimental prototype developed in this study, four building envelope materials were used (a)
 245 precast concrete; (b) brick; (c) prefabricated exterior insulation, finish systems (EIFS) on a metal frame
 246 and; (d) concrete blockwork. Comparisons of the performance of these materials in relation to the 14
 247 assessment criteria were executed in the excel spreadsheets to calculate the composite optimum assembly
 248 (COA) index for the materials. The excel database contains all the relevant pre-polluted indices for each
 249 material based on 14 assessment criteria which are normalized based on the interval scales proposed (Table
 250 4).

251 **4.1 Development of BIM-OfA Logic**

252 Based on the multi-criteria decision modeling (MCDM) principles, the grading system is used in
 253 normalizing the performances in each of the 14 areas for easy aggregation and comparison. As shown in
 254 Table 2, the 14 assessment attributes are classified into four categories viz; ease of assembly, ease of
 255 handling, the speed of assembly and assembly waste.



256
 257 **Figure 3:** Schema for integrating dynamic model with the assessment system

258 Given a 3D digital prototype of a building in a BIM environment, the composite optimised assembly (COA)
 259 index for each building element (External Wall in this case) is expressed as the summation of the product
 260 of the optimised assembly factors “F_i” for the building element and the derived weighted importance “W_i”
 261 of the factors as shown in equation 1;

262
$$COA = \sum_{i=1}^n (W_i \times F_i) \tag{1}$$

263 It is worth noting that the optimized assembly function F_i for a number of assembly factors “i” represents a
 264 function of the optimized assembly score of the four categories of assembly factors, i.e. “OA_{EA}”, “OA_{AH}”,

265 “OA_{SA}” and “OA_{AW}”. These categories are (i) ease of assembly; (ii) ease of handling; (iii) speed of handling
 266 and (iv) waste produced respectively. This relationship is expressed as;

267 **Table 3:** Description of assessment variables

Notation	Description
W_n	The weight of categories from VAHP
F_i	Set of optimised assembly factors i.e $F_i = \{F_1, F_2, \dots, F_n\}$
E_H	Ease of handling parts, components, and connectors
A_w	Waste index of materials & finishes $\{0 \leq A_w \leq 1\}$
S_A	The efficient speed of assembly
Cbp	Type of connection between parts
Ctm	Type of connection to other building elements
R_i	Set of connection properties i.e $R_i = \{R_1, R_2, \dots, R_n\}$
nS_f	The need of on-site secondary finishes
N_j	Set of properties for on-site secondary finishes
fp	The fragility of parts and components
ds	Degree of standardization
np	Total number of parts of building element
ns	Total number of standardised parts
β	Part minimization factor
P	Production rate
\mathcal{A}	Area of walls
ρ	The density of wall material
cl	Cost of assembly labour/craftsmen
cpe	Cost of plant/equipment
G_f	Geometry factor
mt	Total man-hours
nM	Total number of composite material of parts
nE	Number of equipment required for assembly
nW	Number of on-site assembly workers
wp	The weight of loose parts
V	The volume of loose parts
Qp	The degree of on-site sampling of parts for quality

268
$$F_i = f(OA_{EA_i}, OA_{AH_i}, OA_{SA_i}, OA_{AW_i}) \quad (2)$$

269 Thus, we establish the relation of the optimized assembly index “OA_i” for each assessment category to the
 270 composite optimized assembly "COA" index by aggregating the value of the optimized assembly index for
 271 the categories “OA_{EA}”, “OA_{AH}”, “OA_{SA}” and “OA_{AW}”.

272
$$COA_i = \sum_{i=0}^n (f(OA_{EA_i}, OA_{AH_i}, OA_{SA_i}, OA_{AW_i})) \quad (3)$$

273 From Equation 3, the value of the optimized assembly index for the first category (ease of assembly)
 274 “OA_{EA_i}” is expressed as the product of the optimised assembly score for ease of assembly “C_{EA_i}” and the
 275 weighted importance of the category “W_{EA_i}” that was determined through VAHP procedure (see table 6).

276
$$OA_{EA_i} = W_{EA_i} \times C_{EA_i} \quad (4)$$

277 As shown in table 4, C_{EAI} is determined by calculating the summation of the product of factors F_i and the
 278 factors weightings W_{Fi} within the category. The equivalent value F_i is determined using the grading scale
 279 in table 4. The factors depend on independent parameters as explained below.

$$280 \quad C_{EAI} = \sum_{i=1}^6 (W_{Fi} \times F_i) \quad (5)$$

281 The first six factors are used to determine the optimized assembly score for ease of assembly C_{EAI} . The
 282 methods of determining the factors and subsequently, the grading equivalent F_i are explained below.

283 The first factor i.e *connection between parts* "Cbp" of the same element and the second factor i.e *connection*
 284 *to other elements* "Ctm" are used to derive F_1 and F_2 respectively. The parameters for calculating "Cbp"
 285 and "Ctm" are the same and the factors are taken as the mean of the conditional values of a set of properties
 286 $R_i \{R_1, R_2, R_3, R_4, R_5\}$ for the connections as defined in equation 6.

$$287 \quad Cbp = \frac{R_1 + R_2 + \dots + R_5}{n} \quad (6)$$

288 Where $n = 5$ for the set of properties defined as follows; $R_1 = 1$ *If* connector is removable without damage
 289 to parts *Else* $R_1 = 0$; $R_2 = 1$ *If* connector is reusable after removal *Else* $R_2 = 0$; $R_3 = 1$ *If* connector does not
 290 require temporary support after fixing *Else* $R_3 = 0$; $R_4 = 1$ *If* connectors are standardised *Else* $R_4 = 0$, and
 291 $R_5 = 1$ *If* connectors does not involve wet operation on site *Else* $R_5 = 0$. This enables the assessment of
 292 building connectors based on the conditions above, a preferred connector will have the value of 1 with (0
 293 $\leq Cbp$ or $Ctm \leq 1$).

294 Similarly, the third factor i.e *need for on-site secondary finishes* "nSf" is used to derive the grading
 295 equivalent F_3 . The factor is obtained by finding the mean of the values of the conditional set of properties
 296 $N_i \{N_1, N_2, \dots, N_n\}$ as defined in the equation.

$$297 \quad nSf = \frac{N_1 + N_2 + \dots + N_n}{n} \quad (7)$$

298 Where $n = 5$ for the set of properties defined as follows; $N_1 = 1$ *If* secondary finish is not required for
 299 aesthetics *Else* $N_1 = 0$; $N_2 = 1$ *If* secondary finish is not required for thermal insulation *Else* $N_2 = 0$; $N_3 = 1$
 300 *If* secondary finish is not required for moisture control *Else* $N_3 = 0$; $N_4 = 1$ *If* secondary finish is not required
 301 for fire protection *Else* $N_4 = 0$, and $N_5 = 1$ *If* secondary finish is not required for durability enhancement
 302 *Else* $N_5 = 0$. This enables the assessment of building parts based on their requirement for on-site post-
 303 assembly finishing, a preferred material will have the value of 1 with ($0 \leq nSf \leq 1$).

304 The equivalent F_4 , F_5 , and F_6 are determined by the fourth factor i.e *degree of standardisation* " ∂s ", the
 305 fifth factor i.e *multiple material usage* " $n\mathcal{M}$ ", and the sixth factor i.e *geometry* " Gf " respectively. The
 306 degree of standardisation " ∂s " is given as the percentage of the number of standard parts " ns " to the total
 307 number of parts " np ".

$$308 \quad \partial s = \frac{ns}{np} \times 100\% \quad (8)$$

309 The 'multiple material usage' factor " $n\mathcal{M}$ " is simply the number of composite building material of the
 310 parts " γ ".

$$311 \quad n\mathcal{M} = \gamma \quad (9)$$

312 While the geometry factor " Gf " is expressed as the length of the longest side of loose parts " lp " for
 313 assembly of the building element.

$$314 \quad Gf = lp \text{ (metres)} \quad (10)$$

315 From Equation 4, the optimized assembly index for the first category (ease of assembly) " OA_{EA_i} " is
 316 expressed using the derived equivalent value of the optimised assembly score " C_{EA_i} " from the equations
 317 above and the interval grading scale (Table 4). Where " W_{EA_i} " is the weighted importance of the category
 318 and " W_{F_i} " is the weighted importance of the factors respectively.

$$319 \quad OA_{EA_i} = W_{EA_i} \times \sum_{i=1}^6 (W_{F_i} \times F_i) \quad (11)$$

320 The optimized assembly score for ease of handling C_{EH_i} is determined by six factors $F_7 - F_{12}$ and the
 321 respective weighted importance of the factors W_{F_i} . The expression in equation 12 is used to calculate the
 322 optimised assembly score for ease of handling:

$$323 \quad C_{EH_i} = \sum_{i=7}^{12} (W_{F_i} \times F_i) \quad (12)$$

324 The equivalent value of the seventh factor F_7 is determined on the grading scale by the part minimisation
 325 factor " β ". The part minimisation factor is expressed as the ratio of the number of parts " np " to the total
 326 area of the wall " \mathcal{A} ".

$$327 \quad \beta = \frac{np}{\mathcal{A}} \quad (13)$$

328 The equivalent value of the eighth factor F_8 is determined on the terval grading scale by the weight of
 329 loose parts " ωp ". ωp is expressed as a ratio of the density of wall material " ρ " to the volume of parts " v ".

330

$$\omega p = \frac{\rho}{v} \tag{14}$$

331 The equivalent value of factors $F_8 - F_{12}$ are determined by for the number of equipment " nE ", the fragility
 332 of parts " fp ", quality control requirement " Qp ", and the number of workers required " nW " respectively.
 333 These factors are determined through a user-based evaluation using the interval grading scale.

334 **Table 4:** Interval assessment scales (F_i) for grading individual building elements and material

Factors (F_i)		Grading Scale Equivalent (0-5)						
		0	1	2	3	4	5	
C_{EA}	F_1	Connection between parts	0	0.2	0.4	0.6	0.8	1
	F_2	Connection to other elements	0	0.2	0.4	0.6	0.8	1
	F_3	Need for secondary finishes	1	0.8	0.6	0.4	0.2	0
	F_4	Degree of standardization	$\leq 10\%$	11% - 25%	26% - 44%	45% - 65%	66% - 84%	$\geq 85\%$
	F_5	Multiple material usages	≥ 7 material types	6 material types	5 material types	4 material types	3 material types	≤ 2 materials types
	F_6	Geometry	$\geq 0.81m$	0.6m-0.8m	0.45m – 0.59m	0.31m– 0.45m	0.16m– 0.30m	0.02m– 0.15m
C_{EH}	F_7	Number of parts	≥ 13.1	10.1 – 13.0	7.1- 10.0	4.1- 7.0	1.1- 4.0	≤ 1.0
	F_8	Weight of parts	≥ 15.1 kg	12.1 -15.0 kg	9.1- 12.0 kg	6.1- 9.0 kg	3.1- 6.0 kg	≤ 3 kg
	F_9	Tools/Equipment requirement	4 Plants + Tools	3 Plants + Tools	2 Plants + Tools	1 plant + Tools	3 - 5 Tools	≤ 2 Tools
	F_{10}	Fragility of parts	Require specialized or expert handling	Require individual part packaging	Require packaging and special movement tools	Require protective bulk packaging	Require non-protective bulk packaging	Require no packaging or damage protection
	F_{11}	Quality control requirement	$\geq 86\%$	66% - 85%	31% - 65%	16% - 30%	4% - 15%	1% - 3%
	F_{12}	Assembly workers requirement	6 workers or more	5 workers	4 workers	3 workers	2 workers	1 worker
C_{SA}	F_{13}	Production rate	≤ 0.5 m ² /man-hour	0.51 - 1.0 m ² /man-hour	1.1 - 2.0 m ² /man-hour	2.1 - 4.0 m ² /man-hour	4.1 - 6.0 m ² /man-hour	≥ 6.1 m ² /man-hour
C_{AW}	F_{14}	Waste	0.96 - 1.0	0.8 – 0.95	0.6 – 0.79	0.4 – 0.59	0.2 – 0.39	0 – 0.19

335

336 Therefore, the optimized assembly index for the second category (ease of handling) " OA_{EH_i} " is expressed
 337 as the product the derived optimised assembly score " C_{EA_i} " and its weighted importance " W_{EH_i} ".

338

$$OA_{EH_i} = W_{EH_i} \times \sum_{i=7}^{12} (W_{F_i} \times F_i) \tag{15}$$

339 To derive the value of the optimized assembly score for the speed of assembly " C_{SA_i} ", the equivalent value
 340 of the thirteenth factor " F_{13} " is multiplied by the weighted importance of the factor " $W_{F_{13}}$ ".

$$341 \quad C_{SA_i} = W_{F_{13}} \times F_{13} \quad (16)$$

342 The equivalent value " F_{13} " is taken from the interval grading scale based of the production rate "P", which
 343 is a ratio of total work area " \mathcal{A} " to the average man-hour " mt ". To convert the equivalent man-hour mt^*
 344 for on-site equipment, the ratio of the average cost of equipment "cpe" per hour to the average cost of
 345 craftsmen "cl" per hour is used.

$$346 \quad mt^* = \frac{cpe/hr}{cl/hr} \quad (17)$$

$$347 \quad P = \frac{\mathcal{A}}{(mt + mt^*)} \quad (18)$$

348 Therefore, the optimized assembly index for the third category (speed of assembly) " OA_{SA_i} " is expressed
 349 as the product the derived optimised assembly score " C_{SA_i} " and its weighted importance " W_{SA_i} ".

$$350 \quad OA_{SA_i} = W_{SA_i} \times (W_{F_{13}} \times F_{13}) \quad (19)$$

351 The equivalent value of the fourteenth factor " F_{14} " is determined from the interval grading scale based on
 352 the waste index of the materials. A similar expression for calculating the optimised assembly index for the
 353 fourth category (assembly waste) " OA_{AW_i} " is given in equation 20.

$$354 \quad OA_{AW_i} = W_{AW_i} \times (W_{F_{14}} \times F_{14}) \quad (20)$$

355 From equation 3, the composite optimised assembly index " COA_i " is given as the summation of the
 356 optimised assembly index of the four categories viz " OA_{EAI} ", " OA_{EHI} ", " OA_{SA_i} " and " OA_{AW_i} ". Taking the
 357 expressions for the optimised assembly indexes from equation 11, 15, 19 and 20, " COA_i " is given as:

$$358 \quad COA_i = [W_{EAI} \times \sum_{i=1}^6 (W_{Fi} \times F_i)] + [W_{EHI} \times \sum_{i=7}^{12} (W_{Fi} \times F_i)] + [W_{SA_i} \times (W_{F_{13}} \times F_{13})] + [W_{AW_i} \times (W_{F_{14}} \times F_{14})] \quad (21)$$

359 To simplify the equation, the weighted importance of each category and the weighted importance of factors
 360 within the category are multiplied to derive the global weights " W_i ". The resultant expression is given in
 361 equation 1.

362 **5 RESULTS**

363 The section presents the results of the engagement of participants with expert knowledge in offsite
 364 construction and BIM. Experts were engaged based on their experience in BIM design and assessment. To
 365 develop the weighted importance of assessment factors through priority voting, a total of 40 experts were

366 invited for the questionnaire survey, 27 responses were received. The focus of the survey was the depth of
 367 knowledge of participants about the relatively new concepts of BIM-based optimisation in the construction
 368 industry. After examining the 27 responses, 25 responses were valid, and 2 responses were removed due to
 369 incomplete information. This represented a response rate of 62.5%. The participants were from various
 370 backgrounds and worked in the construction industry, many of whom had at least a master's degree and
 371 significant experience.

372 **Table 5:** Background of Expert Respondents

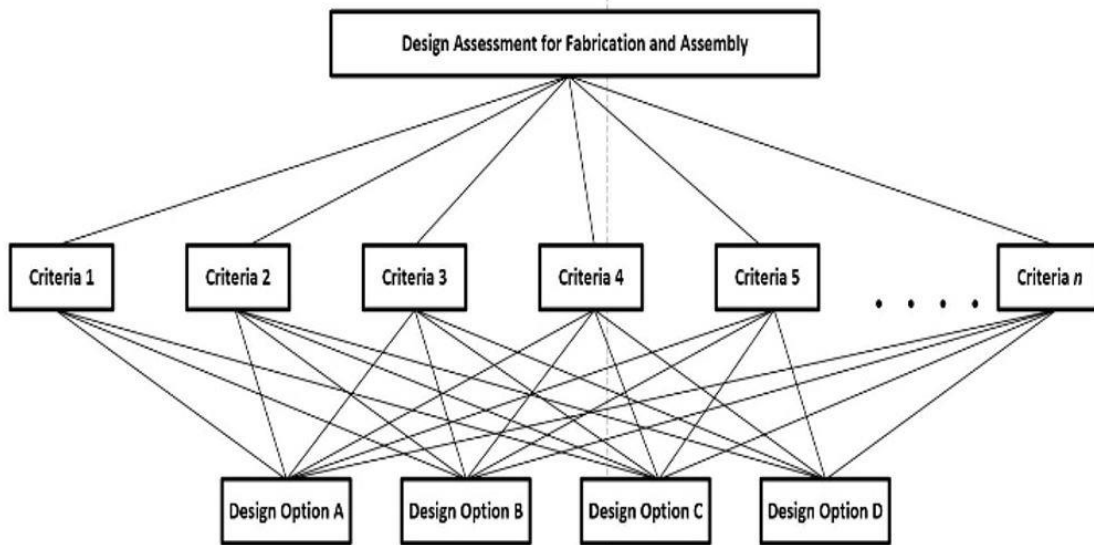
		Frequency (n)	Percentage (%)
Job Description	Architect	5	20.0
	BIM Manager	2	8.0
	Civil/Structural Engineer	6	24.0
	Construction Manager	6	24.0
	Mechanical/Electrical	1	4.0
	Project Manager	3	12.0
	Site Waste Manager	1	4.0
	Others (Lecturer)	1	4.0
Qualification	HND	2	8.0
	Bachelor's Degree	8	32.0
	Master's Degree	10	40.0
	Doctorate Degree	4	16.0
	Other	1	4.0
Years of Experience	1 – 4 years	6	24.0
	5 – 9 years	5	20.0
	10 – 14 years	7	28.0
	Over 15 years	7	28.0

373

374 **5.1 Voting analytical hierarchy process**

375 The analytic hierarchy process (AHP) developed by Saaty, 1987 is a multi-criteria decision method used to
 376 evaluate the relative importance of factors that affect decision making (Saaty, 1987). It quantifies the
 377 relative priorities/weights of a given set of criteria based on the evaluation by a group of experts through a
 378 scaled comparison which indicates the extent to which one criterion dominates another criterion. The
 379 scaling process is then translated into priority weights for the criteria or alternatives. AHP has been widely
 380 applied in several fields of research including construction engineering and management (CEM) (Ameyaw,
 381 et al., 2016) thus indicating its usefulness as a multi-criteria decision method. Despite its utility, AHP has
 382 some limitations that led to the advent of the voting analytic hierarchy process (VAHP) by Liu and Hai
 383 (2005). Prominent amongst the limitations of AHP is the difficulty in applying the paired comparison (Liu
 384 & Hai, 2005), particularly where the criteria are many (Hadi-Vencheh & Niazi-Motlagh, 2011). For
 385 example, 10 criteria yield 40 paired comparisons that can be very laborious, if not infeasible, for decision-
 386 makers. VAHP, instead of using paired-comparison, adopts a vote ranking approach whereby a set of
 387 criteria and sub-criteria in a hierarchical structure is ranked to determine their weights (Liu and Hai, 2005).
 388 Given a large number of attributes identified in this study, the VAHP approach was deemed more

389 appropriate. Additionally, the categorization of the attributes constituted a hierarchical structure, which
 390 lends itself to the use of VAHP for assessment of alternative designs for assembly as shown in figure 2.



391

392 **Figure 4:** Hierarchy of assessment levels using VAHP

393 **Table 6:** Weighted Importance of assessment factors

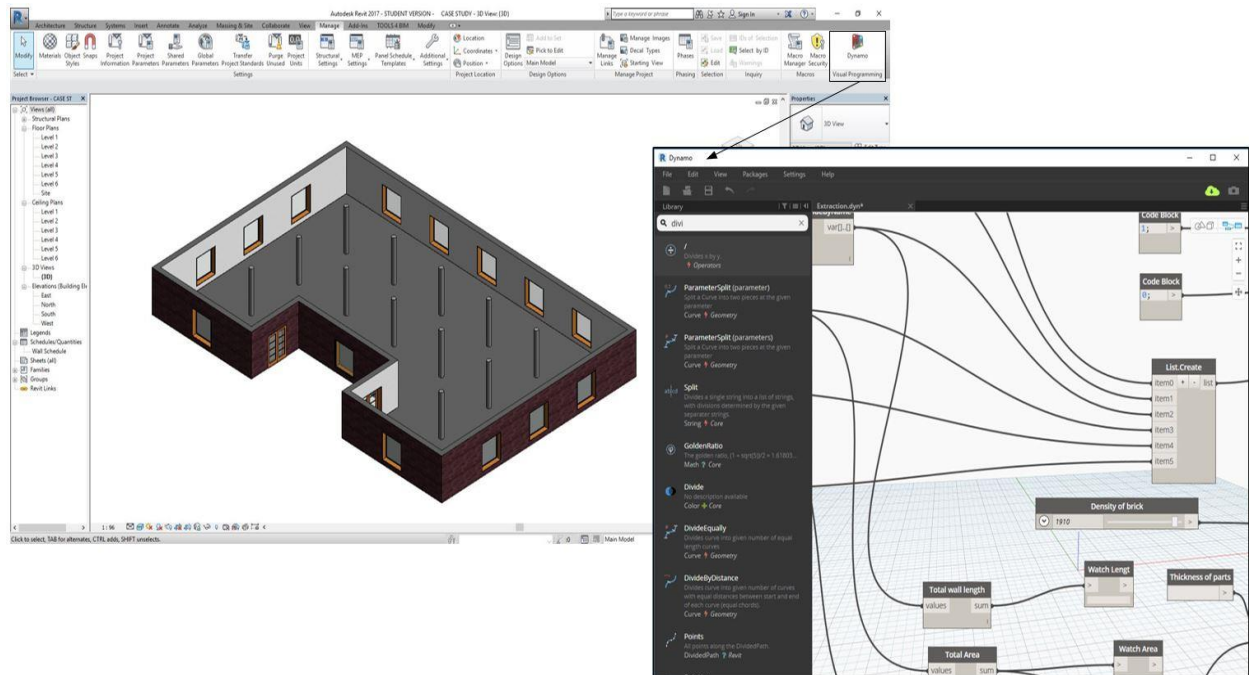
Table 6: Weighted Importance of assessment factors		Categories Weighting (W_{ci})	Factors (F_i)		Factors Weighting (W_{Fi})	Global Weighting (W_i)
Categories (C_i)						
C1	Ease of assembling parts	0.3184	F1	Connection between parts	0.2898	0.0923
			F2	Connection to main building elements	0.2057	0.0655
			F3	Post-assembly secondary finishes	0.1165	0.0371
			F4	Standardization of parts	0.1510	0.0481
			F5	Multiple material usages in production	0.1088	0.0347
			F6	Geometric complexity of parts	0.1282	0.0408
C2	Ease of handling parts	0.2096	F7	Number of parts	0.2101	0.0440
			F8	Weight of parts	0.2882	0.0604
			F9	Tools and equipment requirement	0.1426	0.0299
			F10	Fragility of parts	0.1475	0.0309
			F11	Quality control requirement	0.1069	0.0224
C3	Speed of assembling systems	0.3216	F13	Efficiency of operations	1.000	0.3216

C4	Waste produced in process	0.1504	F14	Waste Index	1.000	0.1504
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394

395 5.2 The Proposed Model

396 The four design options described in section 3.6.2 of the case study was assessed using the assessment
 397 criteria interval (Table 4.1). The case study design options were limited building envelope design in order
 398 to test the applicability of the proposed assessment system. The elements considered were: (i) a precast
 399 concrete wall; (ii) a brick wall; (iii) an exterior insulation wall and a block wall. The digital prototype was
 400 developed in Autodesk Revit. The geometric and material information including the identification of
 401 specific materials was achieved through Dynamo studio. A script was developed to allow the extraction of
 402 basic parameters into an external database. Microsoft Excel was relied on as the external database as a result
 403 of its simplicity. The proposed computational methods were then implemented within the spreadsheet with
 404 conditional formatting that highlighted the best alternative in a specific color. i.e. traffic light signaling was
 405 adopted. A script was further developed through dynamo to override material properties such that it reflects
 406 the color coding from the results of the analysis. Thus, the system provided a design support that highlights
 407 where materials with poor and non-efficient construction and assembly credentials are selected in the design
 408 process.



409

410 **Figure 5:** Extraction of information from digital prototype

411 The VPL tool within the spreadsheet was used to identify and derive some parameters such as the area of
 412 the wall, number of parts, the weight of loose parts and so on (Tauriainen, et al., 2016). Other process-based

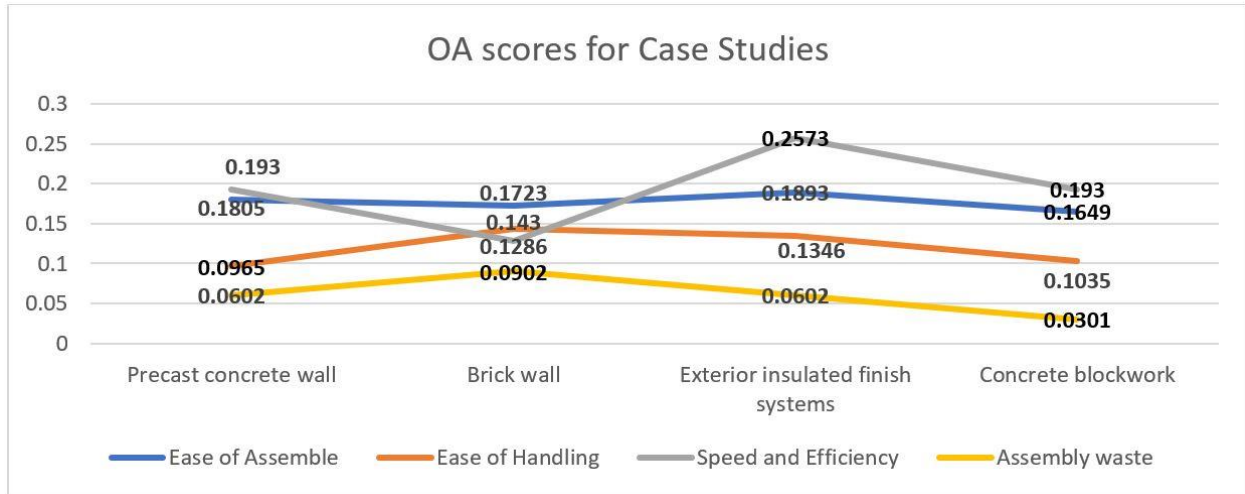
413 and user-based parameters such number of workers, number of equipment, the fragility of parts and so on
 414 (Guy, et al., 2006). The result of the case study assessment is presented in Table 7. The EFIS wall has the
 415 highest efficiency of assembly, this is due to the reduced man-hours and machine-hours on-site, the could
 416 be because of the ease handling and fastening components (Webster & Costello, 2005). However, the brick
 417 wall also has high ease of handling on-site, but it has the lowest speed/efficiency of assembling.

418 **Table 7: COA Score for Case Studies**

Case Study	EA	EH	SA	AW	COA
Concrete Wall	0.1805	0.0965	0.1930	0.0602	0.5301
Brick Wall	0.1723	0.1430	0.1286	0.0902	0.5341
EIFS Wall	0.1893	0.1346	0.2573	0.0602	0.6413
Blockwork	0.1649	0.1035	0.1930	0.0301	0.4914

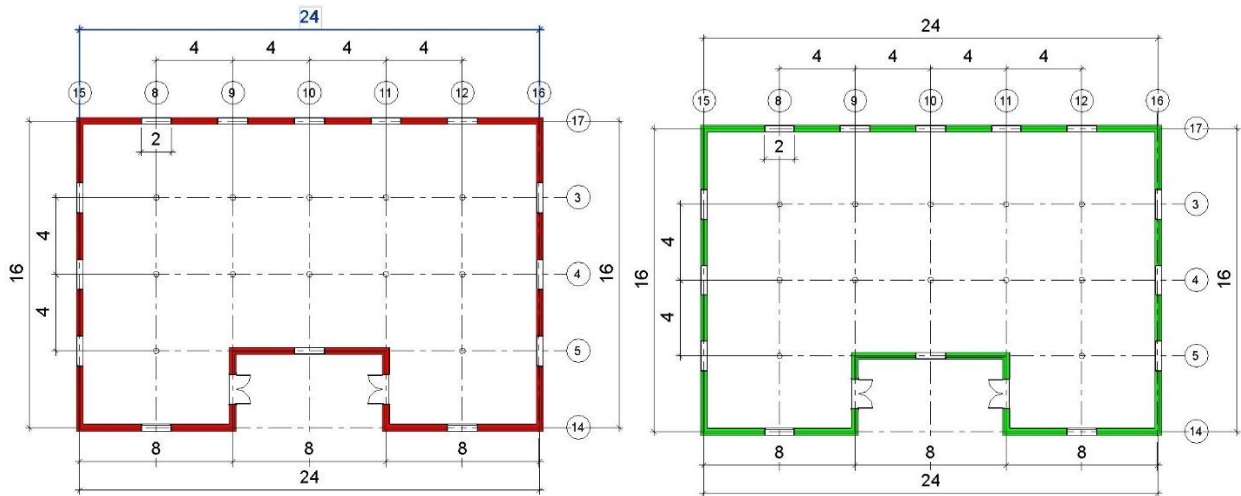
419 (*EFIS- Exterior Insulation Finish Systems, EA-Ease of assembling, EH- Ease of handling, SA- Speed of assembling,*
 420 *AW-Assembly waste*)

421 This means that ease of assembling and ease of handling influences the efficiency positively. The composite
 422 optimized assembly (COA) score was highest for the EFIS material which recorded the highest ease of
 423 assembling and highest efficiency of assembling. In terms of lean efficiency, the use of EFIS wall material
 424 will minimize the duration of onsite operations and the resources used during onsite operations. The brick
 425 wall has second highest COA score due to the high ease of handling which is influenced by the
 426 characteristics of the parts such as size, weight, and fragility. The blockwork material has the lowest COA
 427 score, although the efficiency of assembly is high relative to block work, it has lower ease of assembly, one
 428 of the reasons is because it requires post-assembly secondary finishes when compared to brick. This scoring
 429 system assists designers in knowing the strength and weaknesses of design choices. Also, the scores reflect
 430 DFMA principles and lean principles such as weight minimization, types of connection and so on, and can
 431 be used to assess the degree to which each material aligns with DFMA and lean principles.



432

433 **Figure 6:** Optimised assembly scores for case studies



434

435 (a) Block Wall

435 (b) Exterior Insulation Finish System (EIFS) Wall

436 Colour grading scheme for BIM visualization:

437 Worst: ■

438 Intermediate: ■

439 Best: ■

440 **Figure 7:** Visualisation of Optimal Material in BIM Environment through Colour Coding

441 5.3 Validation

442 This assessment system was evaluated by a panel of six experts with an average industry experience of 15
 443 years and advanced to expert experience in building information modeling and design optimization. A demo
 444 of the assessment system was shown to the experts for evaluation based on the following criteria: (i)

445 Relevance to practice; (ii) Usefulness for industry needs; (iii) Insights for design optimization; (iv) Ease of
 446 application; (V) Ability to enhance continuous improvement, and; (vi) Reflectiveness of assessment results.
 447 Participants were asked to evaluate the system using a Likert scale of (1-5) based on the criteria. The
 448 evaluation results indicate the general acceptance of the design optimization tool, all participants agree or
 449 strongly agree that the tool is relevant to best practice, easy to use and can enhance continuous improvement
 450 in the design optimization. Participants also agree that the tool provides insights for optimizing designs and
 451 that the assessment results reflect the degree of optimization. Table 7 shows the mean score and standard
 452 deviation for the BIM-OfA assessment system from the Likert scale evaluation based on each criterion.

453 Table 8: Average score of the assessment system based on validation criteria

	Question	Average Score (5)	Standard deviation
1	Relevance to practice	4.50	0.50
2	Usefulness for industry needs	4.30	0.56
3	Insightfulness for design optimization	3.83	0.36
4	Ease of application	4.50	0.58
5	Ability to enhance continuous improvement	3.83	0.90
6	Reflectiveness of results	4.50	0.50

454

455 6 DISCUSSION

456 The global construction market is expanding, and forecasts show that it will grow by over 70% by 2025,
 457 the UK Government construction strategy is also keen on achieving £1.7 billion savings on construction
 458 efficiency from 2016 to 2020 (IPA, 2016). This shows the importance of efficiency and productivity in the
 459 construction industry. When compared to the manufacturing industry, the construction industry is very
 460 inefficient (Aziz & Hafez, 2013). This is due to the complexity of construction operations and the inability
 461 to standardize the construction process to enhance repeatability and continuous improvement (BCA, 2016).

462 The adoption of successful practices in the manufacturing industry has shown to have a great influence
 463 on construction processes (Paez, et al., 2005). Lean construction is specifically aimed at reducing
 464 inefficiency in construction operations through process improvement and waste minimization (Aziz &
 465 Hafez, 2013). On the other hand, DFMA is aimed at designing building parts and components in a way that
 466 will enhance easy fabrication and assembling on site (Boothroyd, et al., 2004). This study explored these
 467 manufacturing-based concepts to identify important factors that can enhance design assessment for
 468 optimization during design.

469 This assessment system explored the capabilities of virtual prototyping to assist designers to focus on
 470 detailed elements of design optimization such as connections, geometry, weight and so on. The assessment

471 system also incorporates the importance of parts minimization, standardization, waste reduction, efficiency
472 improvement, and reduction of on-site operations, machines, and workers. The integration of these
473 assessment parameters with BIM also enhances the easy application by designers using visual programming
474 languages for computational design, prototyping, and optimization. From the result, the most significant
475 category is the “ease of assembly” and the most significant attribute within this category is the “connection
476 between parts”. This confirms the use of the “type of connection” in similar frameworks such as Akanbi,
477 et al., (2018) and Akinade, et al., (2015). Also, within the “ease of handling category”, the “weight of parts”
478 was the most significant. This shows the importance of DFMA and lean principles for design decision
479 support by using factors that affect manufacturing and assembly.

480 In view of this, the BIM-OfA assessment system has great potential for improving construction efficiency
481 and minimizing wastage by evaluating design decision using factors that have proven to be useful in the
482 manufacturing context of design optimization (Ekanayake & Ofori, 2004). This will assist designers in
483 understanding the implications that designs have on the manufacturing and assembly process. By improving
484 efficiency through design optimization, designers can contribute to the strategic targets to improve
485 productivity in the construction industry. Future research will develop the system for overall assessment of
486 building designs by computing the composite scores for other building elements such as roofing, slabs,
487 column, beams, and foundations. Also, studies will investigate the overall process of offsite construction
488 and assembly to identify factors of optimization and embed in design optimization tools.

489 **7 CONCLUSION**

490 This study integrates the principles of lean construction and DFMA to develop a design assessment system
491 for design optimization, factors were identified and prioritized to obtain their weighted importance to the
492 overall assessment system. The study categorized the assessment factors into (i) ease of assembling (ii) ease
493 of handling (iii) speed of assembling; and (iv) assembly waste. The results from the priority voting survey
494 show that the speed of onsite assembly process is the most important category for the construction industry
495 experts. Within the ease of assembling category, the properties of parts connectors such as reusability,
496 removability, standardization and so on, is the most important attribute. Also, the weight of parts and
497 number of parts topped the important attributes in assessing ease of handling category.

498 The assessment system was tested within a BIM environment to assess the COA score for four BIM
499 materials for building envelopes. Building envelopes was chosen because of the large proportion it covers
500 compared to other building elements, it is also a building element with many varieties of materials for
501 alternative design selection. The case study was used to evaluate the system performance and the outcome
502 was presented to a panel of six industry experts for validation. The validation results show that the

503 assessment system is relevant to practice and has the potential to enhance the ability of the construction
504 industry in meeting productivity targets.

505 Based on the results of the case study, the construction industry can benefit from the assessment system
506 for efficient material selection, waste minimization during assembly and fast project delivery. The BIM-
507 OfA assessment system will help users to understand and choose design options based on the optimization
508 objectives. Also, BIM-OfA will help users in selecting construction methods and materials based on their
509 unique peculiarities and competencies. Generally, the capability of BIM to create efficient information input
510 and output has made it a good platform for design optimization. Through BIM, process-based information
511 can be used to enhance decision making at early while relying on BIM-based information for the overall
512 improvement of the construction process. This study took advantage of this BIM capability to develop an
513 assessment system for building envelopes. A major limitation of the assessment system is that it is limited
514 to building envelopes and cannot be applied to other building elements. To enable the overall assessment of
515 building systems, a full-scale development of the system is required. Further study is recommended to
516 improve the system and extend its applicability to the real-life overall assessment of all building elements
517 and alternative designs for building element..

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