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A BIM Based Approach for Optimization of Construction and Assembly through Material Selection

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Abstract

During the design phase of construction projects, professionals seldom consider implications of design choices in terms of the ease with which it can be constructed. This contributes to wastage when chosen design features and materials result in the use of inefficient construction production and assembly methods. In order to bridge this gap, this study provides an approach for incorporating production knowledge and data into Building Information Models (BIM) to support optimization of building designs in terms of the efficiencies associated with their onsite production. A building design assessment system is developed to aid selection of alternative building design elements and materials in a digital prototype before they are actually constructed. The assessment system relies on an index derived from production knowledge or data related to ease of assemble, speed of assemble and the waste associated with the assembly or construction of a building element or material. This paper presents the identification and prioritisation of criteria for the development of the index for optimal selection of building envelope systems. The criteria were reviewed by an expert panel (*n*=25) who provided weightings of criteria importance through a voting analytic hierarchy process (VAHP). A schema for implementation through the extension of BIM with external assessment index logic is also presented. The practicality of the system as an indicator of the efficiency with which a design can be built or constructed, provides a solution for leveraging production knowledge and data to improve design in terms of its buildability thereby reducing waste associated with inefficient construction and sometimes redesign or late substitution of materials.

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

1. Introduction

The access to practical information about construction production is important for building design development. However, this information is often absent or inadequate especially at early stages of design conception. Furthermore, design concept is commonly affected at the construction phase of building projects when production information becomes available. This often results in design changes, delays of construction activities and material substitution. According to Boothroyd et al. [1], the efficiency of production processes depends on the decisions made at early stages of design conception. With the adoption of BIM in construction, early stage decision making has been greatly influenced through visualization, clash detection, material quantity take-off and so on [2,3]. However, there is huge data deficit about construction and assembly processes to serve as basis when making early stage decisions [4]. This is due to the complexity of construction operations and the fragmentation within industry. Like BIM, lean construction is gradually closing these gaps of inefficiency with proposition of production methods that eliminate waste [5]. Through lean construction, reliable data can be generated from construction processes while continually improving and standardizing the processes [5]. Also, by adopting Design for Manufacturing and Assembly (DFMA) principles, production data can be used to improve the construction efficiency through early stage design optimization [6,7]. With the ability of BIM to integrate these principles, lean construction and DFMA have great potentials to create continuous improvement in the construction sector [5,7]. This study explored the principles of lean construction and DFMA to develop BIM-based assessment metrics for material selection at early stage design.

2. Literature Review

The efficiency with which building designs are accomplished depends on the quality of information on which the design decisions are made. Designs that are produced without adequate early-stage consideration of the method of construction often create inefficiency during construction [8]. This is the basis of design assessment for constructability [4]. In the manufacturing industry, DFMA and lean principles have been applied to ensure that product designs can support easy manufacturing and assembly of parts [1]. Recently, successful practices in the manufacturing industry are being adopted in the construction industry to meet up the productivity targets of the construction industry [9]. There is also more emphasis on adopting manufacturing principles in construction in order to minimize activities on site which tends to be less controlled environment as compared to factory conditions where manufacturing takes place [7]. It is therefore imperative that designers have the ability to assess the extent to which their designs incorporate these principles [6]. However, these concepts have not been significantly leveraged for the development of knowledge-based assessment frameworks to be applied in design despite the promise of BIM for delivering this [7].

"Lean construction" refers to the adoption of lean production principles in the construction industry and overall helps to reduce/minimize waste in construction process to achieve optimum value [5]. With lean construction, reliable production data can be developed during construction operations and used for design decision making and continuous improvement [5]. The focal point of lean construction is to eliminate waste/inefficiency in construction processes, standardize construction procedure and reduce unnecessary complexity in methods of construction [9]. Lean is therefore dependent on data related to the efficiency and waste associated with production and may include productivity indices, man-hours, machine/equipment productivity and usage rates and so on. Through BIM, this information can be embedded within the digital objects as additional information to support early stage design decisions. Also, DFMA principles are commonly focused on improving ease of manufacturing and assembly from early stage of design. This creates an opportunity to creatively align these principles to maximize the potential benefits through BIM [7].

Assessment of design constructability is common in the construction industry. Some studies used the multi-criteria approach for developing constructability assessment models because of the complex nature of construction [4,8,10]. Constructability assessment criteria from these studies include standardization, minimizing the number of components variations, preassembly engineering, transportation, installation and reviews of specifications. Design constructability can also be assessed based on cost, time, sustainability, safety, and quality indexes [11]. Akinade et al., [2] on the other hand proposed the use of BIM for assessing waste associated with deconstruction. Many assessment models have been applied to improve construction efficiency, however, DFMA and lean principles could be applied to further improve the attainment of theses efficiencies.

Das and kachanapiboon [12] recommended that assessment models should be developed in a way to enhance user-based evaluation and ensure flexibility. Also, assessment tools should use a multiple criteria and scaled grading approach to ensure the adequacy of assessment tools [2,6,12]. Lastly, it is important to integrate the assessment principles as an additional knowledge-base in/attached to parametric design authoring software such as BIM to ensure applicability and practicality [2,7]. These recommendations are applicable in developing an assessment approach based on DFMA and lean principles for material selection in BIM-driven design.

3. Methodology

A three-phase methodology was developed to achieve the aim of the research. In phase 1, following an in-depth literature review on the principles of DFMA and lean construction, assessment factors which could ensure construction efficiency at early stage were identified. These factors were reviewed and prioritized by a panel of experts in the construction industry using priority voting survey. At the second phase, the result from the priority voting survey was analyzed to derive weights for each assessment factor. Also, a scaled interval rating system was developed from literature, surveys, industry reports, building standards and regulations. The scale (0-5) was used to develop the assessment interval using both quantitative and qualitative parameters. At the final phase, the assessment index for a

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case study of four building envelope materials was implemented within BIM to guide the selection of material for the building envelop. The four materials considered for applying the computation logic in BIM were (a) *precast concrete;* (b) *brick;* (c) *prefabricated exterior insulation finish systems (EIFS) on a metal frame* and; (d) *concrete blockwork*.

3.1. Identification of Assessment Criteria

In addition to lean, principles five major methods of DFMA assessment criteria (which is mostly used in product design and manufacturing) were used as basis for the identification of important factors for design optimization. The most recurring factors from this review was size of parts, weight of loose parts and handling difficulty [6]. Other important factors include standardization of parts and connectors, equipment and plant requirement, workforce (productivity) requirement and so on. The identified factors were classified and reviewed for adequacy. Finally, a consolidated list of criteria was derived resulting in a list of 14 presented in the Table 1.

Table 1. Assembly Knowledge Factors for Design Optimization

Categories	Attributes	Design Principle	References
Ease of assembling parts	Connection between parts	Joints should be durable, reusable and multifunctional. Permanent joints that cannot be recovered should be limited.	[2,13,14,15]
	Connection to main building elements	Connections that require a wet operation such as mortar, concrete etc should be minimized. Bolts and nuts are preferable.	[2,6,13,14,15]
	Post-assembly secondary finishes	Design should limit the use of materials that require secondary finishes for aesthetics, durability or fire protection.	[2, 6,13,14,15]
	Standardization of parts	Designer should make use of opportunity to standardize parts and components to enhance mass production and repeatability	[6,13,14,15]
	Multiple material usage in production	Parts with composite materials should be avoided, material variation should be limited.	[2, 13,14,15,16]
	Geometric complexity of parts	Regular and symmetrical shape with adequate tolerance is desirable for parts design to enhance easy assembly.	[2, 13,14,15, 16]
Ease of handling parts	Number of parts	The number of building parts should be minimized as much as possible.	[1, 2, 6,7,14,15]
	Weight of parts	The density of parts should be within the efficient handling capacity of workers and machines to avoid fatigue, accident, damages and assembly errors.	[2, 6, 15,16]
	Tools and equipment requirement	Assembly operations that require the use of too many tools should be avoided, tools should be minimized. multipurpose equipment is preferable.	[8,12]
	Fragility of parts	Fragile parts that require special damage protection and handling should be avoided, parts should be compact and not loose.	[16,17,18]
	Quality control requirement	Complex parts that require expert quality assurance should be avoided unless necessary, design should enable easy quality control and less sampling.	[5,12]
	Number of workers required	The number of assembly workers should be minimized as much as possible through the design of efficient assembly system.	[5,12]
Speed of assembling the whole system	Speed of assembly in relation to labor and equipment cost	The efficiency of the assembly process is determined by the amount of work done with available resources. Efficiency should be as high as possible to minimize resource used and maximize work done.	[5, 13,15,19]
Waste produced during operations	Waste index of parts and applied finishes	Assembly choices with minimum material waste are preferable.	[2, 5, 13,15,19, 20]

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4. Development of Weighted Index for Assessment Criteria

In order to implement any index based on the factors above there is a primary need to weight the criteria in order of importance or contribution to assembly optimization. Thus, quantitative data about criteria importance was ascertained through voting analytic hierarchy process (VAHP) methodology. This was based on a panel discussion and voting survey targeted at experts with extensive knowledge in construction technology as well as offsite manufacturing methods. Although participants with vast experience were targeted, the survey questions were kept unambiguous and easy to respond to [21]. The range of expert experience spanned BIM, lean construction, offsite fabrication and materials. The respondents were purposefully targeted based on their knowledge of the research subject [22]. A total of 40 experts were invited with 25 valid responses received at the end of study. The job description of respondents included Architects, BIM Managers, Project Managers, Waste Managers, Mechanical and Electrical Design Engineers. The factors shown in Table 1 were ranked in order of importance relative to their contribution to most efficient construction. This ranking was used to develop the weightings for the multi-criteria assessment indices for assembly for the materials in the case study. The participants were required to cast priority votes for each of the assessment criteria as well as sub-criteria.

Table 2. Background of Expert Respondents.

		Frequency	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 Engineer	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

4.1. Weighting of Assessment Criteria Based on Expert Input

The expert priority voting survey was used to establish the relative importance of the 14 criteria for design assessment for fabrication and assembly. The prioritization presented relates to building envelop systems construction given this was chosen as the case material for implementing the proposed system in this study. The criteria were grouped into four areas namely, *ease of fabrication and assembly, ease of handling parts/components*, *productivity* and *waste generated*.

These criteria are used to develop the assessment indices to compare the relative degree to which the design options satisfy each criterion. Every valid response contained votes to rank the criteria position (for example 1^{st}, 2^{nd}, 3^{rd}, or 4^{th}). The sum of votes for each criterion is shown in Table 3. The weight of the criteria and sub-criteria was determined using Hadi-Vencheh and Niazi-Motlagh’s [23] VAHP equation. The rank of each criterion was determined using these weights; “speed of assembly” had the highest rank, “waste generated” had lowest while “ease of assembly” and “ease of handling parts” have ranks ‘second’ and ‘third’ respectively.

The same procedure was used to determine the ranks of the sub-criteria. The normalized weights are obtained for the twelve sub-criteria, the sum of weights from each category is equal to one. The global weight for each of the assessment factors was determined by multiplying the weight of each sub-criteria by the weight of the criteria. These Global weights can be used directly as part of the computation logic is comparing different material types based on their performance and capabilities with respect to each of the 14 factors adopted for implementing this system. The performance and capabilities is assessed based on scaled assessment interval metric.

Table 3. Weighted importance of assessment criteria (***Wi***).

Categories	Weight (*Wi*)	Attributes	Weight (*Wi*).	Global Weight (*Wi*)
Ease of assembling parts	0.3184	Connection between parts	0.2898	0.0923
		Connection to main building elements	0.2057	0.0655
		Post-assembly secondary finishes	0.1165	0.0371
		Standardization of parts	0.1510	0.0481
		Multiple material usages in production	0.1088	0.0347
		Geometric complexity of parts	0.1282	0.0408
Ease of handling parts	0.2096	Number of parts	0.2101	0.0440
		Weight of parts	0.2882	0.0604
		Tools and equipment requirement	0.1426	0.0299
		Fragility of parts	0.1475	0.0309
		Quality control requirement	0.1069	0.0224
		Number of workers required	0.1048	0.0220
Speed of assembling systems	0.3216	Efficiency of operations	1.000	0.3216
Waste produced in process	0.1504	Waste Index	1.000	0.1504

*4.2. **Development of Scaled Assessment Grading System***

A scaled interval was developed to assist designers in evaluating and quantifying the characteristics of each design options (materials). Based of multi-criteria decision (MCDM) modelling principles, the grading system is used in normalising the performances in each of the 14 areas for easy aggregation and comparison. Three methods of data development are used to develop the evaluation scale viz; (a) Existing literature and product information, quantitative and qualitative inquiry from experts; (b) Customisable inputs, which allows a designer in making a subjective user-based evaluation with respect to desired design requirement and; (c) The rule-based method which incorporates design and construction rules identified from the discussions with experts. The proposed structure of this grading/scaling system was also validated by the experts engaged in the study. For brevity, example of scales adopted for four out of the 14 assessment criteria is presented in Table 4.

Table 4. Examples of interval assessment scales (***Ci***,*)* for grading individual building elements and materials.

Attributes	Measure	**Grading Scale Equivalent (*Ci*)**					
		0	0.2	0.4	0.6	0.8	1
Connection between parts	This attribute is evaluated based on Removability (R1), Reusability (R2), Stability (S_1), Standardization (S_2) and Dryness during operation (D). See Table Notes (a)	0	0.2	0.4	0.6	0.8	1
Degree of standardization	This attribute is evaluated by finding the percentage number of standard parts in total number of parts in the design options.	≤ 10%	11% - 25%	26% - 44%	45% - 65%	66% - 84%	≥ 85%
Weight of parts	This attribute is evaluated using the density and volume of part material. Equation provided within the system determines the computation of the relative weight of parts for scaled evaluation.	≥ 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
Production rate	The production rate for each design option is assessed based on the quantity of work that can be completed in a unit labour-time. Mechanical equipment-time is converted to labour/cost equivalent.	≤ 0.5 m^2/man-hour	0.51 - 1.0 m2/man-hour	1.1 - 2.0 m2/man-hour	2.1 - 4.0 m2/man-hour	4.1 - 6.0 m2/man-hour	≥ 6.1 m2/man-hour

For brevity, we present below example of computation logic for the assessment criteria and overall index aggregation.

(a) The formula (Equation 1) below is used to calculate the grading value for building element relative to the attributes such as connection between parts (Attribute 1) and connection with other building elements (Attribute 2).

$$\textit{Type of Part Connection} = \frac{R1+R2+S1+S2+D}{5} \tag{1}$$

(Where ***R₁=1***, *if the connector is easily removable without damaging connected parts and* ***R₁=0*** *if connector cannot be removed without damaging parts.* ***R₂=1***, *if connector can be reused if removed from assembly and* ***R₂=0***, *If connector cannot be reused.* ***S₁=1***, *If connectors require no temporary support after fixing to attain stability and* ***S₁=0*** *if connectors require temporary support,* ***S₂=1***, *If connectors are standardized and* ***S₂=0*** *If connectors require special production specification.* ***D=1***, *if the connection does not involve wet operation and* ***D=0***, *If the connection requires wet operation).*

(b) The Formula (Equation 2) below shows how the composite index of overall optimal design is computed based on the aggregation of computations for each of the 14 factors with respect to each building element (material).

$$\textit{Composite Optimum Assembly Index Computation} = \sum_{i=1}^{14} W_i \times C_i \tag{2}$$

(Where ***Wi*** is the weighted importance of criteria *and* ***Ci***, *rating point (i.e. 0 to 5) on grading scale based on material properties/performance).*

4.3. ***Implementation of Assessment Logic in BIM for Design Optimisation***

The logic proposed is based on a comparison of different material options within a BIM (Autodesk Revit) environment with the aid of computations and knowledge stored in an external database (Microsoft Excel) relative to each material and its performance based on the grading scheme presented above. Open source, visual programming extension (Dynamo) is used to query basic information (i.e. material/element type and attributes such as geometry or quantities) from the Revit BIM model into the external database as demonstrated in Figure 2. The tools selected to implement the logic is as a result of its interoperability. For the experimental prototype developed in this study, four building envelope materials were used ((a) *precast concrete;* (b) *brick;* (c) *prefabricated exterior insulation, finish systems (EIFS) on a metal frame* and; (d) *concrete blockwork*. Comparisons of the performance of these materials in relation to the 14 assessment criteria, as well as an overall aggregate assessment (based on Equation 2) are then executed in the excel spreadsheets. The excel database contains all of the relevant indices for each material based on 14 assessment criteria which are normalized based on the interval scales proposed (see examples in Table 4).

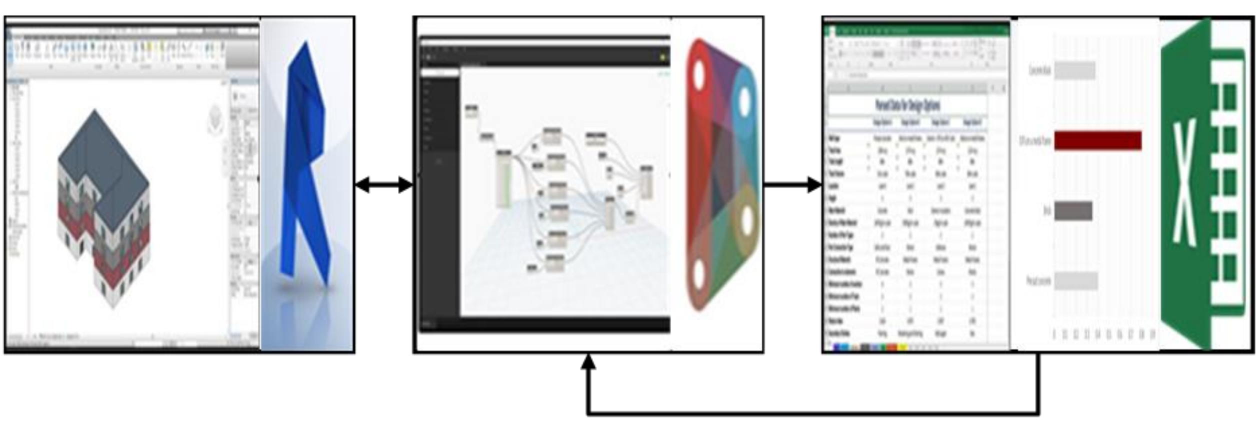

Fig. 2. Implementation of logic in BIM environment

The outputs from this is then interpreted using scripts written in Dynamo for visualization within the Revit environment. Designer can select which material or element types they require a comparison on in the database. For a comparison of any set of selected elements types or materials the best is highlighted based on a color coding protocol representing a range from the best to the worse alternative. Designers can also revise database as information especially on context dependent factors such labour productivity or plant availability. Existing element properties relating to geometry are relied on though this can still be altered in the database.

5. Discussion

An in-depth review of the literature revealed the lack of design optimization tools that are based on principles of successful practices in the manufacturing industry. The manufacturing industry is far more efficient than the construction industry because of best practices such as DFMA and lean production as well as their assessment [5,6,7,15]. Despite the proliferation of constructability/buildability [8,24,25,26], deconstruction [2,15], and waste estimation [2], none of such tools were based on principles such as DFMA and lean neither have they been developed from a perspective of design optimisation. Constructability and buildability assessments have also normally focussed on traditional construction processes where principles of offsite and DFMA or lean are not given the desired focus. From the empirical findings, factors related to speed and ease of assembly are regarded as paramount with the type of connections used to integrate building elements emerging as one of the individual most important factors. Similar criteria have been highlighted in previous studies [2,5,6,7,15,24,25,26,27]. In this study, it has been demonstrated that design can be optimised using information and data as a knowledge-base through its formalisation into assessment indices.

6. Conclusion

The aim of this research was to adopt DFMA and lean principles for the development of a design optimization method for construction. To achieve this aim, literature was reviewed to extract optimization factors for building construction and assembly. It was discovered that, despite the recent and gradual adoption of DFMA and lean in the construction industry, there has been no significant attempt to develop assessment metrics that ensure their integration with BIM to influence choices at the design phase. The factors were prioritised through a voting analytic hierarchy process (VAHP) as part of the development of an index for optimal selection of building envelope systems within a BIM environment. A schema for formalisation of this concept through the extension of BIM with the assessment logic is also presented. It is demonstrated that BIM can serve as a knowledge-base of production related information which can be leveraged at the design phase for lean and assembly optimisation. Future tools can evolve to cover other building elements in addition to building envelope, as well as fully automate the logic through developments of embedded plugins or programmes with the support of Application Programming Interface (API) of BIM tools.

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