Design for Manufacturing and Assembly: Perspectives in Construction

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Abstract

Design for Manufacturing and Assembly (DfMA) is known as both a philosophy and a methodology whereby products are designed in a way that is as amenable as possible for downstream manufacturing and assembly. As construction is moving towards a combination of offsite prefabrication and onsite assembly, DfMA is gaining momentum in this heterogeneous industry that has long been characterized as project based. Nevertheless, a comprehensive review of DfMA in construction, its prospects and challenges in particular, seems absent from the literature. This study reviews the processes and principles of DfMA, and explores the possible perspectives of DfMA exist in the construction industry. It was found that DfMA and Lean construction share common grounds in general principles. Second, DfMA in construction has been interpreted from three perspectives: (1) a holistic design process that encompasses how structure or object will be manufactured and assembled guided with DfMA principles; (2) an evaluation system that can work with virtual design and construction (VDC) to evaluate the efficiency of manufacturing and assembly; and (3) a game-changing philosophy that embraces the ever-changing to prefabrication and modular construction technologies. This study also suggests that development of design guidelines, forming multidisciplinary team, use of VDC systems, and understanding the lean principles are factors that could further the successful application of DfMA in construction.

Keywords: Design for Manufacturing and Assembly (DfMA); Construction; Design; Prefabrication; Assembly; Lean Construction

1. Introduction

Ballard and Howell (1998) described construction on site as a combination of fabrication and assembly. The extent of site assembly depends upon the degree of prefabrication and level of customization required to cater for buyers' choice (Gann 1996). Many studies have explored various aspects of prefabrication, or otherwise known as offsite manufacturing, including its business models (Goulding et al. 2015; Pan and Goodier 2011), barriers and constraints (Blismas et al. 2005; Mao et al. 2013), benefits (Blismas et al. 2006) and opportunities (Arif et al. 2012; Goodier and Gibb 2007). However, a report from KPMG (2016) cautioned '*offsite manufacturing alone will not overcome the challenges the construction industry is facing, to do so requires a partnership with an integrated design process, like the Design for Manufacturing and Assembly (DfMA) method*'. DfMA analysis method is commonly known as methodological procedures for evaluating and improving product design for both economic manufacturing and assembly. Unlike the increasing uptake of lean thinking (originated in manufacturing) by construction firms to improve the construction process, very few studies (Fox et al. 2001) attempted to shed light on best practices of design engineers, the building designer's counterparts in manufacturing, in the design stage such as the DfMA method. As Dewhurst

(2010) noted, '*what we have forgotten along the way is that the design of the product itself ultimately controls the total cost.'* DfMA can guide cost reduction efforts early in the product design process, so that product's full potential of lean production can be realized since some potential manufacturing problems and assembly issues have already been addressed in the design. The aim of this paper is to review critically the concepts and principles of DfMA, to discuss the perspectives of DfMA in the construction industry, and to suggest key strategies for better implementation of DfMA in construction.

2. Review of DfMA

2.1. DfMA: Concept

There are two components of DfMA, design for manufacture (DfM) and design for assembly (DfA) (Bogue 2012; Otto and Wood 2001). DfM is principally concerned with making individual parts, DfA addresses the means of assembling them (Bogue 2012). The research on DfA is pioneered by Boothroyd and Dewhurst (1987) who conducted a series of studies considering the assembly constraints during the design stages. Based on the premise that the lowest assembly cost can be achieved by designing a product that can be economically assembled by the most appropriate assembly system. The key principle is to produce design with fewer parts as well as designing the parts which remain easy to assemble (Stoll 1986). To achieve that, Boothroyd and Dewhurst's handbook (1987) designed various ratings for each part in the assembly process based on the part's ease of handling and insertion. In the construction context, the implication of DfA concept is to consider how aspects of the design can be designed in a manner that minimizes work on site, and in particular, avoids 'construction' (RIBA 2013). An example would be designing a handrail system that allows half landing lengths to be quickly installed into sockets which are pre-positioned in the stair structure (RIBA 2013).

DfM, on the other hand, compares the use of selected materials and manufacturing processes for the parts of an assembly, determines the cost impact of those materials and processes, and finds the most efficient use of the component design (Ashley 1995). O'Driscoll (2002) defined DfM as the practice of designing products with manufacturing in mind, with its goal is to reduce costs required to manufacture a product. Interestingly, O'Driscoll (2002) argued that the principle of DfM is at least 200 years old, citing LeBlanc, a Frenchman, devised the concept of interchangeable parts in the manufacture of muskets which were previously individually handmade (Bralla 1999). For construction, DfM is the process of designing in a manner that enables specialist subcontractors to manufacture significant elements of the design in a factory environment (RIBA 2013). Panelised system such as claddings have been designed in this manner for years, and now the emerging hybrid systems (i.e. pods) and modular buildings (i.e. fully factory-built houses) also pertain to the DfM concept.

From the above descriptions of DfM and DfA, it was felt that these two disciplines are appropriate to be considered together, as one term - DfMA (Bogue 2012). This is because products now are complex and the ability to assemble them effectively is equally critical. Constance (1992) noted that DfMA was a management and software tool enables designers to consider a product's material selection, design, manufacturability, and assembly up front. Boothroyd (2005) outlined the original DfMA analysis method which provided methodological procedures for evaluating and improving product design for both economic manufacturing and assembly. When DfMA was introduced to manufacturer such as Douglas aircraft in California, it was labelled as a design review method that identified the optimal part design, materials choice, and assembly and fabrication operations to produce an efficient and cost-effective product (Ashley 1995). The goal is to provide manufacturing input at the conceptualization stage of the design process in a logical and organized fashion.

2.2. DfMA: Process and principles

The typical DfMA process can be arranged into stages, as summarized in Figure 1. Boothroyd (1994) has noted that DfA should always be the first consideration, leading to a simplification of the product structure. This is followed by economic selection of materials and processes and early cost estimates. In this process, cost estimates for original design and new (or improved) design will be compared, in order to make trade-off decision.

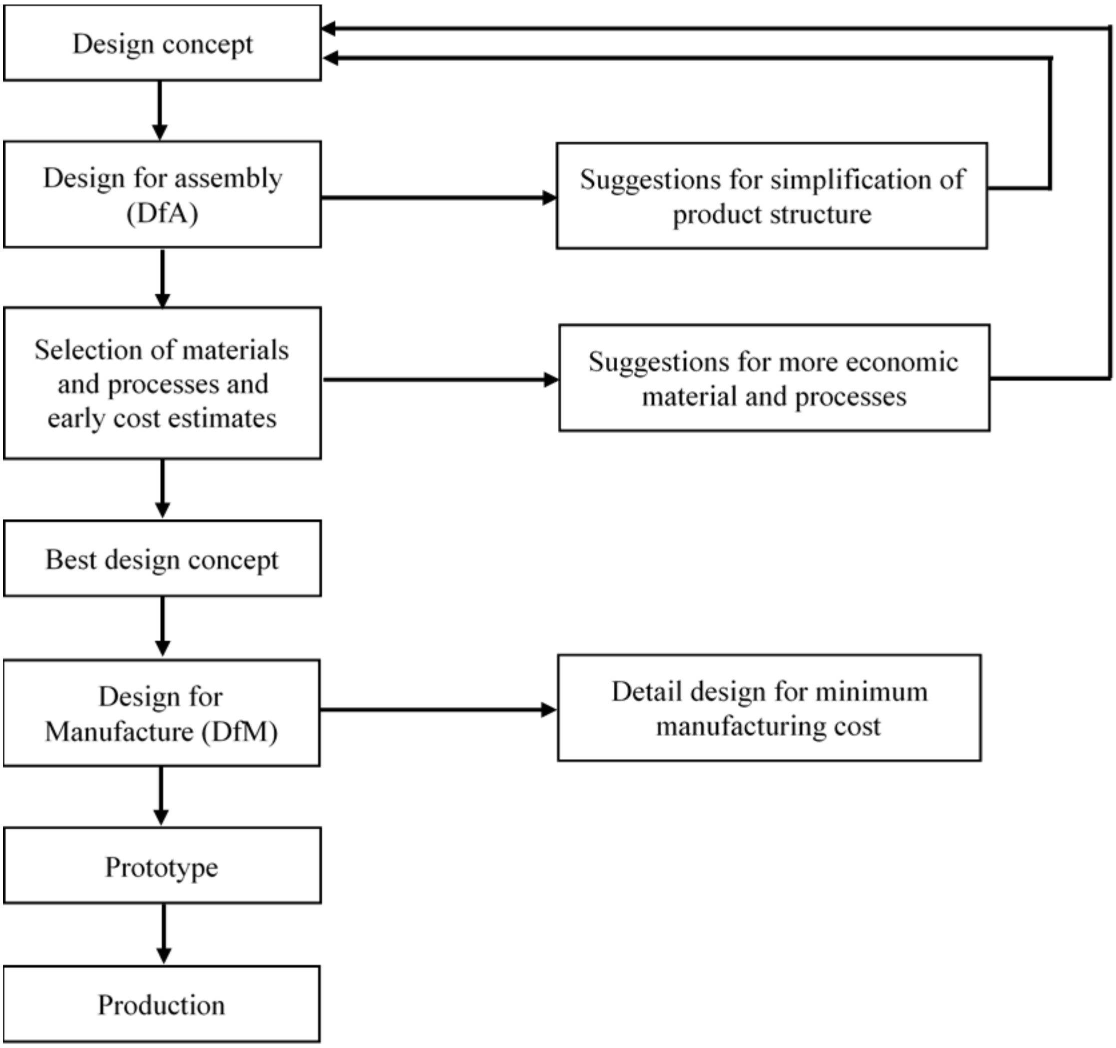

Figure 1: Typical stages in a DfMA procedure. Source: Boothroyd (2005)

Fox et al. (2001) noted that design engineers are provided with standard design improvement rules or guidelines in workbooks and standard design evaluation metrics in manuals for evaluating a design with respect to its ease of assembly. If a concept is compatible with these guidelines, one can be reasonably assured that the design will be fairly well in the subsequent detailed analysis (Otto and Wood 2001). In this manner, a feedback loop is provided to aid designers measuring improvements resulting from specific design changes (Boothroyd 2005). Afterwards, the best design is taken forward to a more thorough analysis for DfM, where detailed design for the parts will be performed (Boothroyd 1994).

According to Bogue (2012), there are three means of applying a DfMA process. The first is to follow a general set of non-specific and qualitative rules or guidelines and require someone (most likely designers and engineers) to interpret and apply them in each individual case. The aim is to encompass a diversity of products, processes and materials. Table 1 provides an example of such DfMA guidelines and their associated benefits. Similarly, Stoll (1986) outlined ten DfMA principles and rules: (1) minimizing total number of parts, (2) developing a modular design, (3) using standard components, (4) designing parts to be multifunctional, (5) designing parts for multi-use, (6) designing parts for ease of fabrication, (7) avoiding separate fasteners, (8) minimizing assembly directions, (9) maximizing compliance, and (10) minimizing handling.

Table 1: General DfMA guidelines and their benefits

Guidelines	**Benefits**
1. Minimise the part count	Improved reliability, reduced purchasing and inventory costs, simplified assembly
2. Use standard, off-the-shelf parts rather than custom components	Reduced costs, lower purchasing lead times, potentially greater reliability
3. Minimise and standardise the use of fasteners/design for efficient joining and fastening	Reduced costs, simplified assembly, improved reliability, simplified repair and maintenance
4. Use as few dissimilar materials as possible	Simplified jointing, fewer manufacturing processes
5. Minimise the use of fragile parts	Cost reductions due to fewer part failures, easier handling and assembly
6. Do not over-specify tolerances or surface finish	Easier manufacture and reduced fabrication costs
7. Design for ease of fabrication	Cost reductions from the elimination of complex fixtures and tooling
8. Consider modular designs	Reduced costs due to simplified assembly and test
9. Aim for mistake-proof designs	Cost reductions by eliminating need to re-work incorrectly assembled parts
10. Design for simple part orientation and handling	Cost reductions due to non-value-added manual effort or dedicated fixturing
11. Design with predetermined assembly technique in mind	Cost reductions from use of proven/known techniques
12. Consider design for automated/robotic assembly	Potential cost reduction over manual methods

Source: Bogue (2012)

A close examination reveals that despite these guidelines/principles from various reference points, they share substantial similarities, such as minimization, standardization, and modular design to be the key characteristics of DfMA principles. This is in line with the heuristic principles of Koskela's (2000) flow concept of production: (1) simplify by minimizing the number of steps, parts and linkages, (2) increasing flexibility, and (3) increasing transparency. As Koskela (2000) noted: *'simplification can be realized, on one hand, by eliminating non-value-adding activities from the production process, and on the other hand by reconfiguring value-adding parts or steps.'* The implication of this heuristic principle, in the context of DfMA, is for designers to rethink their designs as to what extent the criteria that they applied in their designs would affect the production and assembly that may cause extra motions.

The second method employs a quantitative evaluation of the design. The rationale is that each part of the design can be rated with a numerical value depending on its 'assemblability' (Bogue 2012). Subsequently, the numbers can be summed for the entire design and the resulting value is used as the guide to evaluate the overall design quality. Another evaluation tool is based on a 100-point method with demerit marks being given for factors which hamper the ease of assembly.

The third approach which is most recently developed, is the automation of the entire process. It relies on computer software. Quantitative analysis can be applied to the design, followed by constructing an expert system employing the general design rules. The system can be developed in a way that a design can be analysed, evaluated and then optimized by repeatedly by applying the rules and improve the design quality after each iteration. In this situation, it is particularly important that the DfMA ruled based evaluation tool is linked to production database (Fox et al. 2002).

3. DfMA: Construction perspectives

Construction on site is portrayed by Ballard and Howell (1998) as a combination of fabrication and assembly. Industrialization initiatives are believed to be the driver to shift as much work as possible from site construction into shop conditions where it can be done more efficiently (Ballard and Howell 1998). The key to mass production in construction is not the continuous assembly line, rather, it was the complete and consistent interchangeability of parts and the simplicity of attaching them to each other (Crowley 1998). Since Koskela (1992) brought the production theory into construction, much has been written about lean concept and lean tools to make the site assembly efficient (Tommelein 1998). However, discussions around how design or production development contributes to a better manufacturing and assessable was limited, even though Ballard and Howell (1998) described construction is '*essentially a design process in which the facilities designed are rooted-in-place, and thus require site assembly.*' Given the limited source of DfMA in the construction literature, this paper identified three emerging perspectives of DfMA in construction after a detailed review of literature, followed by a summary of typical benefits that DfMA could promise to the construction industry.

3.1. DfMA: A systematic process

First, DfMA was viewed as a systematic procedure, which can add value to the construction/production process by standardizing component and reducing design variabilities (Goulding et al. 2015). Pasquire and Connolly (2003) documented a 3-step DfMA process that Crown House Engineering[1] adopted for mechanical services installations.

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[1] Crown House Engineering became part of Laing O'Rourke in 2004 and today is one of the UK's leading building and infrastructure technology services providers, supplying a complete Building Services package.

- Step 1 - It begins with a generic intent to use manufactured components and an understanding of the benefits and limitations of pre-assembly products.
- Step 2 - design process comprises four main activities: (1) understanding the interfaces between the structure and the services ensuring design integration, (2) feasibility study of the selection of products, components and pre-assembly unit system, (3) development of the design process programme and identification of coordination activities, and (4) preparation of manufacturing drawings and involvement of supplier specifications, and the coordination of the manufacturing input.
- Step 3 – the manufacturing phase is the final step which comprises of three activities: (1) factory assembly, (2) releasing the manufactured components by signing-off the production checklists, and (3) on-site installation.

Apart from the documented DfMA process on building services design and assembly, Gerth et al. (2013), based on the principles of DfMA and lean, developed the 'Design for Construction' (DfC) method with the following four steps (see Figure 2) in relation to the ordinary project such as private house project. The presented steps of DfC method is only taking place in the concept development and design stage, which is in line with the process of DfMA in the manufacturing literature. It is interesting to see this method encourages designers to capture the production experience from past projects and use it during design.

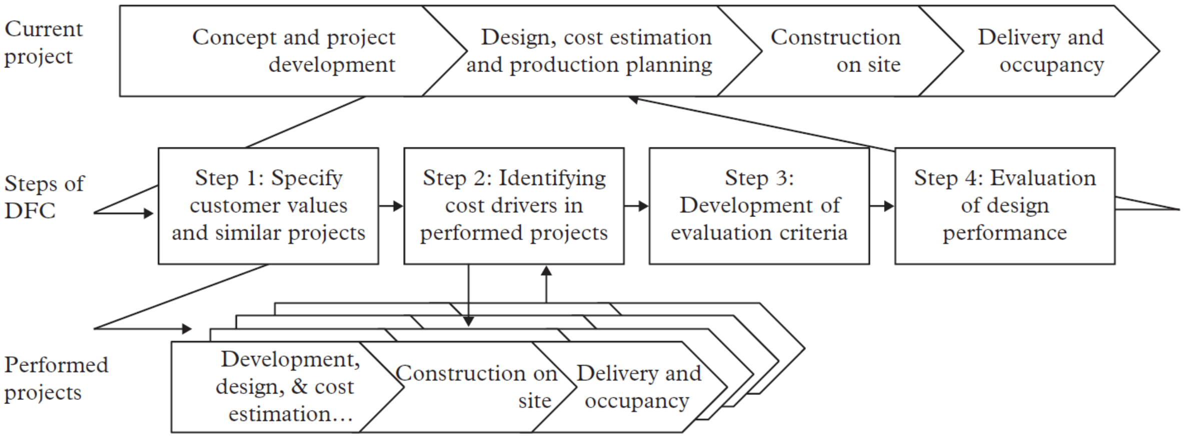

Figure 2: The four steps of DFC and their placement in the housing project process
Source: Gerth et al. (2013)

3.2. DfMA: An evaluation model

Secondly, DfMA is the development of an evaluation method. Leaney (1996) concluded that the real achievement of DfMA methods is their ability to provide measurements of assemblability which allows objective criteria to be applied in a team-based situation. Hence, calculating an assembly index for each part to see how production cost, time and quality are affected, is desired. Leaney (1996) provided insights of three leading DfMA evaluation methods, namely Hitachi method, Boothryd-Dwehurst method, and Lucas method. A comparison is summarized in Table 2.

Table 2: Comparison of three different DfMA evaluation methods

Evaluation methods	**Aim**	**Indices**	**Key features**

Hitachi method	To assess design quality or the difficulty of assembly operations, and to estimate assembly cost improvement	Assemblability evaluation score, E Estimated assembly cost ratio, K.	Defining the motions and operations Filling of a form in the order as the anticipated assembly sequence
Lucas DFA	To assigning and sum penalty factors associated with potential design problems	Three assemblability indices Design efficiency Feeding ration Fitting ratio	The penalty factors and indices give a relative measure of assemblability difficulty. This method is not based on monetary costs
Boothryd-Dwehurst	To establish the cost of handling and inserting component parts whether this is done manually or by machines	DFA index Total number of parts The ease of handling, insertion, and fastening of the parts	A paper based evaluation Answering questions about potential handling difficulties, size, weight and amount of orienting Answering questions about insertion restrictions

Source: adapted from Leaney (1996)

Caution was also voiced out by Leaney (1996) that these methods focused on mechanical based assemblies of a size that could be conveniently assembled at a desk top. It may seem that these methods and procedures are not applicable to products with the size of prefabricated components, or modular units. However, various types of the indices, and evaluation procedures are still worth exploring, which might add value to the body of knowledge in appraisal method of design performance on downstream construction. Apparently, the closest counterpart of 'assemblability' in construction, is buildability which is regarded as both a 'design method' as well as a 'design objective' (Fox et al. 2001). Fox et al. (2001) noted '*process complexity is seen as a barrier to defining buildability, and production design procedures associated with buildability remain largely informal and reliant on intuitive application'*. Singapore's 'Buildable Design Appraisal System' (BDAS) perhaps is the only tool available to quantify the effect of buildability on construction productivity (Jarkas 2015). In BDAS, key components such as structure, and wall components were enumerated with a corresponding labour-saving index. In another word, each value is given to a design choice, and the total value determines the level of buildability. The higher the buildable score would indicate a more efficient use of labour in construction. In the most recent code of practice of buildability (BCA 2017), bonus points are allocated for the use of a number of DfMA technologies. The scoring system allows product designer and building designer, in the case of buildability, to take advantage of opportunity to redesign based on the numerical values. This requires insight and knowledge of the building designers. However, Poh and Chen (1998) clarified that the corresponding labour-saving value for BDAS is derived from undocumented site productivity studies on various design systems, and represents the aggregated wisdom of a panel of experts. Besides the quantification of buildability in construction, Gerth et al.'s (2013) DfC aims to improve constructability and to minimize the number of components, parts and materials that need to be processed, assembled, and handled onsite. To achieve that, a performance index was created to evaluate to what extent the design could achieve the predefined criteria, which is given a factor of relevance (R), and a grade (G). By multiplying the factor of relevance (R) and the grade (G), the total points (P) is obtained for each criterion. The evaluation is done from a waste creating approach on the premise that each case specific evaluation criterion can create many types of waste and is attached with negative effects (Gerth et al. 2013). A case study of wall solution can be found in Gerth et al. (2013).

3.3. DfMA: Prefabrication technologies

Lastly, DfMA was closely associated with prefabrication (Laing O'Rourke 2013), to which a bundle of gaming changing technologies that can be applied (BCA 2016). Royal Institute of British Architects RIBA (2013) defines DfMA as an approach that facilitates greater offsite manufacturing, thereby minimising onsite construction. More specifically, RIBA (2013) noted that DfMA harnesses a wide spectrum of tools and technologies, including (1) volumetric approaches, (2) 'flat pack' solution[2], (3) prefabricated sub-assemblies. Similarly, in Singapore, the DfMA concept was interpreted in a similar fashion. It was first recommended as a key recommendation during the International Panel of Experts (IPE) for construction Productivity and Prefabrication Technology in 2014 (BCA, 2014), where the panel called for fundamental changes and stronger measures in the 2nd construction productivity roadmap to achieve its target of 20-30% construction productivity improvement. This means designing for labour efficient construction, with as much construction works done off-site as possible. Subsequently, BCA showcased some examples of DfMA technologies that are commonly used in construction projects (Table 3).

Table 3: Some DfMA elements (BCA, 2016)

DfMA elements	Note
1. Cross Laminated Timber (CLT)	Manufactured from wood, harvested from sustainably managed forests, and fabricated by binding layers of timber at 90 degrees with structural adhesives to produce a solid timber panel; Able to be used as either structural or non-structural components in buildings
2. Integrated Prefabricated M&E	Mechanical, electrical and distribution items prefabricated either as linear lengths, flat assemblies or integrated within volumetric modules
3. Precast & Prefabricated Elements	Elements that are manufactured in a controlled environment and that are generally of better quality than in-situ elements (e.g. staircases, facades, refuse chutes, parapets etc.)
4. Prefabricated Bathroom Unit (PBU)	A bathroom unit fabricated and preassembled off-site complete with finishes, sanitary fittings, bathroom cabinets, concealed pipework, conduits and ceiling before being delivered and installed in position on site

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[2] Flat pack' solutions, which output a kit of parts that can be quickly assembled on site.

5. Prefabricated Pre-Finished Volumetric Construction (PPVC)	Assembly of whole rooms, modules or apartment units complete with internal finishes and fixtures that are prefabricated off-site and installed on-site to form modular apartments

A comparison of BCA's interpretation of DfMA against the four levels of offsite (Table 4) classified by Gibb and Isack (2003), suggests that the Singapore's approach in incarnating DfMA to prefabrication, is to portray prefabrication as game change technologies. Tan and Elias (2000), however, cautioned the high dependence on technology may cultivate a posture of technological passivity.

Table 4: Levels of off-site

Level	**Category**	**Definition**	**Singapore's DfMA elements**
1	Component manufacture & sub-assembly	Items always made in a factory and never considered for on-site production	
2	Non-volumetric pre-assembly	Pre-assembled units which do not enclose usable space (e.g. timber roof trusses)	Cross Laminated Timber (CLT); Integrated Prefabricated M&E
3	Volumetric pre-assembly	Pre-assembled units which enclose usable space and are typically fully factory finished internally, but do not form the buildings structure (e.g. toilet and bathroom pods)	Precast & Prefabricated Elements; Prefabricated Bathroom Unit (PBU)
4	Whole buildings (modular)	Pre-assembled volumetric units which also form the actual structure and fabric of the building (e.g. prison cell units or hotel/motel rooms)	Prefabricated Pre-Finished Volumetric Construction (PPVC)

Source: Gibb (1999) and Gibb and Isack (2003)

3.4. DfMA: Typical benefits

The benefits of DfMA in manufacturing and construction are of similar fashion. Ashley (1995) cited a survey of DfMA users conducted by Boothroyd Dewhurst Inc. found the typical results include: a 51 percent reduction in parts count, a 37 percent decrease in parts cost, 50 percent faster time-to-market, a 68 percent improvement in quality and reliability, a 62 percent drop in assembly time, and a 57 percent reduction in manufacturing cycle time. More successful stories of applying DfMA can be seen in Boothroyd (1994). The main highlight is that in each case, a considerable reduction in part count has been achieved, resulting in a simpler product (Boothroyd 1994). Similarly, in construction, it was reported, the first major benefit of DfMA is a significantly reduced construction programme (Laing O'Rourke 2013) followed by better quality and safety. RIBA (2013) found 20%-60% reduction in construction programme time, and greater programme certainty. Chen and Lu (2018) noted the DfMA-oriented curtain wall (CW) design was able to save more than 7 mins in terms of assembly time of one

CW unit with better workmanship. A small selection of the reported DfMA case studies in construction, mainly from the UK are shown in Table 5.

Table 5: Examples of DfMA applications in construction

Parties involved (Contractor)	**Project type**	**Off-site**	**Application of Digital Technology**	**Location**	**Key features of DfMA**
Laing O'Rourke	Salford and Wigan Building Schools	70%	Yes	Salford, UK	• Development of a library of standard st components • DfMA development including prefabric service risers, prefabricated services ho distribution units and packaged plantro
Laing O'Rourke	Water Treatment Plant	300 'module transportable packages'	Yes	Queensland, Australia	• Offsite pre-assembled piping and electr distribution 'modules' • 5 plant locations, 32 module groups, 26 modules in total including kits-of-parts
Mott Macdonald	Davyhulme Wastewater Treatment	5000 precast elements	Yes	Manchester	• Development of a catalogue of more th DfMA products, predominantly for the sector, including all the elements neede create a sewage pumping station as wel more general components. • Close liaison between the design discip ensure each component provides the ne structural and functional requirements
Laing O'Rourke	Leadenhall Building	85%	Yes	London, UK	• First time used DfMA in earnest • 20 revisions before a final version was in terms of floor systems
Carillion and Skanska	Battersea Power Station site redevelopment (Phase I)	Manufactured 540 utility cupboards	Virtual-reality	Slough, UK	• The "kit of parts" construction system • Manufacturing takes place in a tempora facility, rented for the duration of the of programme

Source: AECOM (2017), Built Offsite (2017), Enzer (2015), Construction Manager (2015), Laing O'Rourke (2013), and RIBA (2013)

4. Discussion

4.1. Building designers and design guidelines

Boothroyd (1994) used a metaphor 'over-the-wall' approach to describe the design process where the designer throws the design over a wall to the manufacturing engineers who then have to deal with the various manufacturing problems arising because they are not involved. The application of DfMA overcomes this problem by breaking the 'wall' so that designers can consult manufacturing engineers at the design stage (Boothroyd 1994), and later forming proprietary methodologies to help them in design (Fox et al. 2001). Therefore, design engineers are in an improved position to comprehend the requirements of manufacturing including the implication of design decision on quality and cost (Hong et al. 2005). In the building industry, the traditional design can be described as 'designing from first principles' where the design process comprises progressive layering with successive levels of details until all materials are specified and their incorporation are represented on working drawings (Pasquire and Connolly 2003). Mechanical & Electrical (M&E) service tends to be detailed much later than structure and fabric elements and usually well into the construction phase. This is the stage where production and assembly problems are likely to occur and hence requests are made for design changes (Boothroyd 1994). Unlike their counterparts in manufacturing, the building designers have not been provided with equivalent methodologies, but rely on the varying experience of individuals (Fox et al. 2001), and some think in frames (Atkin 1993). The consequence of these is that designers may not be considering all reasonable potential design solutions, and therefore, may overlook something which may be worth having (Atkin 1993). Worse, as Bröchner et al. (2002) put it, the architect and engineers lacked knowledge of exact number of parts, order of assembly, how parts are supposed to be assembled, and how long an on-site operation takes.

Clearly this observation suggests that DfMA has not been applied. Fox et al. (2001) explained little formal (reference) material that is either used or needed during the early design stage. Therefore, DfMA rules, principles, and best practices should be communicated to building designers. A good way to begin with is the development of design guidelines. Edwards (2002) concluded that design guidelines are one of the main sources of explicit knowledge on the practice of design. Gerth et al. (2013) added that DfMA utilizes deep production knowledge and experience from multiple disciplines, functions as a feedback loop between the design and the manufacturing. Each operation takes time and has an associated cost (Edwards 2002). Therefore, qualitative and general principles of DfMA, together with Koskela's (2000) flow principles, can be a good reference point for construction firms to customize their own DfMA guidelines. Some principles may be already known by the designer. Other principles can be triggered by tasks or events as the design proceeds (Edwards 2002). Royal Institute of British Architects (RIBA 2013), being the pioneer, lent its weight to the DfMA approach by creating an overlay to the RIBA Plan of Work 2013 that suggests how architects could weave offsite considerations into all stages, from strategic definition to handover and building use. In Singapore, Building & Construction Authority (BCA) has identified the DfMA approach as a key strategic thrust to raise the construction productivity, and published the prefabricated prefinished volumetric construction (PPVC) guidebook as the first instalment of a series of guidebooks on DfMA technologies (BCA 2017). Association and authority in the UK and Singapore have been forerunners to promoting the DfMA methods through guidebooks published for the industry.

4.2. Multidisciplinary team

Many researchers (Ashley 1995; Omigbodun 2001) emphasized that the DfMA practice is applied by a multidisciplinary, including design engineers, manufacturing engineers, shop floor mechanics, suppliers' representatives, and specialists in production support, maintainability, and reliability. Syan and Swift (1994) wrote the chief among the underlying imperatives of DfMA approach is the team or simultaneous engineering approach in which all relevant components of manufacturing system, including outside suppliers, are made active participants in the design effort from the start. Fox et al. (2001) argued that in construction, only a few modes of building procurement will permit suppliers, subcontractors and consultants to meet during the early stages ode the design process. Chen and Lu (2018) pointed out it is easier to apply DfMA to projects delivered by Design-Build than to Design-Bid-Build project. Similarly, Song et al. (2009) agreed that early involvement of subcontractors and suppliers do face challenges in the contracting practices, but their case studies (Song et al. 2009) showed that fabricators are able to provide design assistance in optimization, modularization, and standardization in the early design stage. Dainty et al. (2001) proposed an integrated contractual system that ensures a parity of responsibilities and obligations would be desired. Chen and Lu (2018) acknowledged it is challenging to balance between benefits/value derived from multi-disciplinary team to integrate knowledge as extensively as possible. But more importantly, the client organization and the architect need to accept that contractor and/or subcontractors can bring added value to their design process.

4.3. Building information modelling (BIM)

Historically, one of the DfMA thrusts is the development of a variety of computer-based and/or computer-aided design programs (i.e. CAD software) (Stoll 1986). Edwards (2002) pointed out that most of the DfMA procedures in manufacturing settings today are computerized. The advantage of computer support is that it aids the DfMA evaluation procedure by prompting the user, providing help screens in context and by conveniently documenting the analysis (Leaney 1996). Once essential data is entered, various analysis, for example the ‘what if’ analysis, are conducted to identify problematic areas as priorities for redesign. In construction, it is reasonable to believe that BIM can be critical to the success of DfMA (Cousins 2014). BIM can be exploited in the design and manufacturing of prefabricated components (Nawari 2012; Vähä et al. 2013) where in the 3D model, all individual building components are digitally available and their geometry as well as behavior and properties are accurately represented. Chen and Lu (2018) reflected in their DfMA oriented curtain wall design case which was developed by using AutoCAD, and noted, the manual process of updating and reanalysing the design (i.e. recalculating the material cost) could have been improved by a more advanced digital parametric design platform. To tap on the potential of BIM for DfMA design, Yuan et al. (2018) proposed a DfMA oriented parametric design, which uses BIM as digital platform, for prefabricated buildings. This novel design approach, as Yuan et al. (2018) claim, realises the coordination of building designers, manufacturing designers, and assembly professionals. The very first task of this design approach is to timely integrate the detailed information required by manufacture and assembly stages of precast component into design stage, i.e. geometry, structure, connection, manufacture process, assembly process, mechanical equipment (Yuan et al. 2018). Given all the associated information needed for the analysis of cost, structure, and assembly, this provides various opportunities to evaluate the ‘assembly’ efficiency, and feeds into the learning loop for continuous improvement purpose (Nawari 2012). Again, the challenge here is the quality of the data or information that needed for BIM to assist the building designer to evaluating alternative designs as Fox et al. (2001) did caution that building designer have limited confidence information (i.e. price books, manufacturer data) when they get it but based on habit. Yuan et al. (2018) argued, architectural design firm can be dominant party in the design team, but they have to cooperate with the other two parties, namely manufacturing and assembly technicians.

4.4. Synergy of DfMA and Lean to gain efficiency

It has been noted, key characteristics of DfMA rules are in line with the heuristic principles of flow concept of production (Koskela 2000). For a successful application, Fox et al. (2002) suggested target DfMA rules on best available productivity/quality improvement opportunities. For example, it seems both DfMA and lean recommended “standardisation” as one common principle to gain efficiency.

Gerth et al. (2013, p.141) wrote '*the key focus in DfMA is to reduce the production cost, mainly by reducing the number of parts, with the aim of reducing the number of assembly operations and the complexity in production management.*' As Koskela (2000) implied other things being equal, the very complexity of a product or process increases the costs beyond the sum of the costs of individual parts or steps. Kremer (2018) noted, not only is parts standardisation important to DfMA, the removal of elements and a reduction in the number of overall parts assist in reducing time in manufacturing and improving efficiency. This question, however, is what needs to be simplified, and how. According to Fox et al. (2002), the best opportunity of standard component designers/producers are to design their components for ease of manufacture, consolidation of parts, and simply assembly. Another example comes from Gerth et al.'s (2013), in which the second step is to identify typical problems and waste on site by using the data collection methods. For example, the seven types of waste (Ohno 1988) can be good examples to look for (Gerth et al. 2013). By understanding what these wastes (non-value adding) activities are, it would be more meaningful to assist designers in understanding what kind of inefficient motions, and operation are associated with manufacturing and assemble. The production knowledge will help the building designers to evaluate how well the desired product characteristics can be achieved with the minimum of waste on site.

5. Conclusion

There are two main areas of manufacturing that construction can benefit from (Kagioglou et al. 1998), namely the design and the production processes. Much has been discussed on the second area. This paper concentrates on the first, with a focus on design for manufacturing and assembly (DfMA). This study begins with a review of DfMA in the manufacturing, and notes DfMA takes manufacturing and assembly into account during the product design, but also these considerations must occur as early as possible. The review of general principles of DfMA reveals that these principles are actually in line with the heuristic principles of Koskela's (2000) flow concept of production. Through a literature review, this paper discovered that DfMA can be deployed in three forms:

(1) A holistic design process that encompasses how structure or object will be manufactured and assembled guided with sets of principles;
(2) An evaluation system that can work with virtual design and construction (VDC) to evaluate the efficiency of manufacturing and assembly; and
(3) A game-changing philosophy that embraces the ever-changing to prefabrication and modular construction technologies..

This paper makes the following contributions. It adds to the body of DfMA knowledge in the construction industry. It extends the previous work of Fox et al. (2001) and Gerth et al. (2013), which only focus one of the perspectives discussed above, by proposing the application of DfMA in construction need to embrace these three perspective holistically. Arguably, the last perspective which views DfMA as prefabrication technologies can quickly enable project team experience many benefits (i.e. reduction in construction programme time). However, taking off DfMA as effective and collaborative design process, together with an evaluation system are equally important as these are originally adopted in manufacturing. In the modern-day construction industry, with the rise of prefabrication and BIM, building designers should be working closely with engineers and fabricators, in a multidisciplinary team, to develop DfMA guides and evaluation metrics and digitally incorporated them into 3D model so that such useful information can assist building designers evaluating alternative designs. Prior to this, the 'over-the-wall' approach in design must be broken down by bringing the knowledge from the parties in the downstream up to the design stage. Early involvement or teamwork avoids many of the problems that arise.

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