DfMA in Building Design and Construction: Uses and Abuses

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Abstract

The phrase 'Design for Manufacture and Assembly' (DfMA) has recently garnered significant attention in the literature and practice of the emerging field of industrialised construction. However, in the translation from its manufacturing origins to this new context, the term 'DfMA' has lost clarity and become somewhat of a catch-all in the discourse around the future of building. This paper examines some of the complexities in transposing DfMA principles, guidelines and methods to the building industry by examining the peculiarities and challenges of the field, and discussing how they might inform an augmented approach for the design and production of buildings.

It can be argued that documented DfA and DfM success in the manufacturing industry has been the result of more than just its general philosophy. Design optimisation has been achieved through manufacturing-specific design guidelines and evaluation metrics comprised within the DfMA process, detailing how best to fabricate and assemble parts in a factory. Unlike most manufacturing scenarios, however, industrialised construction involves multiple sites of production extending beyond the precision of the factory environment to the inherent variability of the construction site. Issues specific to the assembly of buildings such as scale and the interfaces between factory and site, between precise building components and imprecise ground, are not addressed in existing DfA methodology and vastly exceed the intentions and scope of its inventors and key theorists.

And yet DfMA's currency is stronger than ever in building discourse and practice. This paper uses findings from a literature review as well as ongoing research with industry partners in the field of building design and production to discuss how DfMA might be extended for use in this new context. The first step must involve recognition of the differing nature of factory and site assembly, with a focus on data collection within the field as a way of quantifying their differences and informing appropriate future design guidelines.

Key Words

Design for Manufacture and Assembly (DfMA), Industrialised Construction, Design, Prefab, Constructability, Buildability, Lean Construction, Building Production.

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Introduction

The building design and production industry has been increasingly scrutinised for its low productivity, slow technological uptake and inefficient practices.[1] In the recent push to industrialise construction, Architecture, Engineering and Construction (AEC) professions have sought guidance from the methods, theories and vast empirical knowledge base developed in the manufacturing industry. Originating in the manufacturing context, Design for Manufacture and Assembly (DfMA) has been identified not only as one such avenue for potential cross-disciplinary insight, but as a main avenue for industrialising construction itself.

DfMA can be described as a set of design guidelines combined with an evaluation and optimisation methodology (now even in the form of software) for improving the design of a product with respect to how it is made. DfMA methods inform decision making at the design stages with the objective of reducing cost without sacrificing quality, primarily through reduced part count and reduced assembly time. The Boothroyd Dewhurst DfMA software has been used by a broad range of companies such as Dell, Motorola, Harley-Davidson[2] and many more, with published case studies indicating that application of the tools have enabled streamlining of products with reduced production cost and assembly times.[3]

DfMA methods respond to the compartmentalisation of knowledge that resulted from the forces of industrialisation: increasing diversity of manufacturing technologies and capabilities, divisions of labour, increasing specialisation of professions and the geographical separation of design and production.[4] Within the field of building production, a similar condition can be observed. The "reorganisation of knowledge"[5] due to the separation of the design and construct functions of the 'Master Builder,' combined with the increasing complexity of architectural products and systems[6] has resulted in the fragmentation of specialised disciplines within the building design and production process[7]. The individuals involved in the design and production phases of a project typically belong to "separate companies with widely divergent cultures."[8] The collection of building designers (architects, civil engineers, environmental engineers, façade engineers etc.) working on any given project are no longer experts of the material and construction systems involved in turning their conceptions into reality. As a result, design decisions made in the conception of a project may result in construction challenges with cost implications down the line.

Considering DfMA's success in addressing this problem within the manufacturing industry, it is no surprise that the phrase has received significant attention in the field of building production. A recently published literature review has revealed a rapidly increasing interest in DfMA within the building production disciplines. Gao, Jin and Lu report that of the 26 Scopus articles referring specifically to DfMA in construction, 9 were published since 2018.[9] Many large companies in the AEC space now have DfMA-dedicated pages on their websites[10] and in 2013 the Royal Institute of British Architects (RIBA) released a DfMA overlay document for their Plan of Works[11]. In the media, DfMA has taken on buzzword status in the discourse around the future of construction. However, in the translation from its manufacturing origins to this new context, the term 'DfMA' has been opened up to various new interpretations[12], and in doing so lost clarity. This paper proposes that DfMA as found in manufacturing is not entirely appropriate for direct translation to the field of building production, as indicated by the blurring of its definition in this new context.

Conversations around DfMA in both manufacturing and construction contexts are often conducted in the space of engineering, dominated by design methods geared towards optimisation and a scientific design process. This paper aims to unpack the various facets of DfMA as it pertains to the design and production of buildings - the scale and nature of which vary greatly from the manufactured products DfMA was originally developed for. Such a discussion must draw together various aspects affecting the production of buildings in this new industrialised context including: the relationship between factory production and site assembly; the relationship between small scale internal constraints and large-scale external limitations; and an understanding of transport and lifting logistics. Furthermore, additional important qualitative objectives such as safety and design-value are introduced, as well as the importance of mediating the differences between 'designerly' and scientific modes of designing.

The high-level perspective on DfMA within construction presented in this paper has been informed by a literature review and the authors' own experiences drawn from R&D projects conducted with industry partners based on the Industry-University research model. The authors operate out of a research lab spanning the Architecture and Engineering faculties at Monash University, founded on interdisciplinary collaboration and varied research methodologies combining qualitative and quantitative methods.

How is DfMA defined in the manufacturing context?

In manufacturing, DfMA is defined as a "systematic procedure"[13] or a "discipline whereby products are designed so as to be as easy and cost effective to produce as possible."[14] Within this discipline, several different techniques have been developed (such as the Hitachi Assembly Evaluation Method, the Lucas DfA method and the Fujitsu Productivity Evaluation System)[15] however, this paper mainly refers to the Boothroyd and Dewhurst method as it seems to be most prevalent in the literature.

DfMA in manufacturing involves three modes of application. The first is a set of qualitative design guidelines and rules in the form of basic principles to be interpreted and applied by the designer. For example, "Design parts that have end-to-end symmetry and rotational symmetry about the axis of insertion."[16] The second, which Bogue asserts was invented by Boothroyd and Dewhurst[17], involves a quantitative evaluation method using metrics based on the physical attributes of the object which will affect 'assemblability.' The third involves a software version of the above which automates the process to optimise the product.

How is DfMA defined in the building design and production disciplines?

In contrast to the specificity and rigour associated with the terms 'discipline' and 'systematic procedure', the definitions of DfMA in the construction context tend to lean towards softer terms such as 'philosophy' and 'approach':

- "DfMA is an approach which allows designers to maximise value for clients, maintain control over the delivery of their designs and facilitate the adoption of emerging methods, materials and technologies in construction best practice."[18]
- "The DfMA approach redefines the traditional phases of project delivery. This means agreeing and locking down the design phase much earlier to allow the manufacturing, assembly, testing and commissioning phases to be compressed and run in parallel, rather than in one long linear sequence."[19]
- "DfMA […] is a system that takes the process of off-site manufacture one step further by identifying the most cost-effective material early in a structure's design, to speed construction and reduce costs."[20]

The most predominant interpretation of DfMA in the AEC industry refers to an altered production strategy with prefabrication at its core[21]; ultimately, an industrialised approach to construction. Singapore's *Buildability Code of Practice* refers to 'DfMA technologies' along a 'DfMA continuum' which includes a range of prefabrication strategies from simple structural steel components and use of mass engineered timber, prefabricated walls or slabs, unitised curtain walls through to fully finished volumetric modules.[22] This is also true of the *RIBA Plan of Works Documen*t, which states that "DfMA encompasses many techniques, including: volumetric approaches […]; flat pack solutions […]; prefabricated sub-assemblies,"[23] however the document goes on to state that "adopting a DfMA approach does not always mean that standard or manufactured elements need to be adopted. It may simply mean harnessing design rationalisation, materials optimisation, just-in-time delivery or logistics planning in order to achieve high rates of productivity."[24] Banks et Al. extend the definition by emphasising the importance of logistics, including delivery scheduling and use of cranes, as well as how safety measures are embedded within the design of assembly sequence.[25]

Digital technologies such as BIM are seen to be integral to the application of DfMA in construction. Kremer proposes a Design for Mass Customised Manufacture and Assembly (DfMCMA) framework which involves the use of BIM platforms (to cut out processes like producing shop drawings) as well as early involvement of stakeholders through a block-chain platform which could facilitate transparency and accountability. BIM also plays a key role in Liang O'Rourke's DfMA model, which defines DfMA as the convergence of three components: 3D models for visualisation, drawing production and numerical control; BIM analysis; and off-site production.[26] It is worth noting that where DfMA in manufacturing is a tool fed by an established database, BIM is merely the technology with which analysis might be performed – without relevant and accurate data to inform the analysis, it is not comparable.

Banks et al. refer to Liang O'Rourke's approach to DfMA as an evolving mechanism that is directly tied to the business model and improved with each project.[27] Unfortunately the methodology used to capture and feed project learnings back into the business' DfMA model is not mentioned, nor the degree to which this is actually done. In this case, DfMA is cast as intellectual property that gives a particular company an edge over their competitors. This view is supported by the fact that the other techniques mentioned earlier (such as the Hitachi Assembly Evaluation Method, the Lucas DfA method and the Fujitsu Productivity Evaluation System) are all named after commercial companies.

DfMA and Buildability: They are not the same.

In 2001 Fox, Cockerham and Marsh defined Design for Manufacture (DfM) as a methodology for integrating production best practice into designs, arguing that the UK construction sector had no equivalent methodology at the time.[28] Their research identified that buildability was the closest thing in construction, encompassing a 'philosophy' towards design and production, however its limited success was partly due to the absence of a formal design method and measurable production objectives comparable to DfM.[29]

Within the field of building production, constructability is defined as "a system for achieving optimum integration of construction knowledge in the building process."[30] Buildability is a subset of constructability, and refers specifically to the application of construction knowhow in the design phase of a building in order to facilitate ease of construction. Unlike DfMA, buildability is typically not widely disseminated in the form of rules supported by design strategies. Its limited success in practice can be attributed to a combination of factors including a lack of shared understanding of best practice in construction; lack of manuals on material, component or process data for qualified comparisons between the alternatives; lack of metrics for comparative evaluation and lack of collaboration between manufacturing, assembly and plant companies add others.[31] Furthermore, constructability knowhow is derived from current practice within construction which may be superseded in the shift towards an industrialised approach facilitated by the application of methods such as DfMA.

Application of DfMA in construction

Within the literature, approaches to operationalising DfMA in building design and production are focused around three primary objectives: identifying and obtaining relevant production information to inform design decisions (often looking to existing work on buildability), developing methodologies for applying production knowledge in the design process and investigating optimisation techniques.

Design for Construction (DfC), a DfMA-inspired method, looks to existing buildings as source material for buildability best practice[32]. DfC responds to the absence of an agreed methodology for capturing and transferring on-site production experience from completed buildings to the design of new projects in the construction industry. The method proposes that waste analysis from previous projects should be one of the main aspects considered in the development of evaluation criteria for new designs, and that investigation into the management of craftsmen's work on site is key. The framework is based on four steps: (1) identifying similar completed projects to use for evaluation metrics (2) identifying the on-site waste and cost drivers for those particular projects (3) determining criteria to evaluate constructability and (4) evaluating the proposed design. The method aims to enable identification of frequent problems and waste in similar projects in order to assist in the design and evaluation of new projects.

Learning from DfMA, Fox, Marsh and Cockerham propose that "improvements to the ways in which constructability rules are formulated and presented could facilitate their wider application and increased success."[33] Informed by the success factors of DfMA guidelines, they posit that value could be added to existing constructability knowledge by focussing rules on particular design stages in the design sequence; developing explicit strategies for their application; providing databases to support the rules and outlining routine application methods for the rules to be implemented in the design process. Fischer and Tatum identify that the construction knowledge required at the different stages of the design process require varying levels of detail, and outline a framework for capturing and classifying constructability knowledge in a format which would benefit designers at these different stages.[34] The method proposes that buildability information would be more useful if divided into five different knowledge categories: application heuristics, layout information, dimensioning, detailing and exogenous knowledge. Pulaski and Horman develop a Conceptual Product/Process Matrix Model in which constructability information is plotted against project phase on one axis and level of detail on the other.[35] Interestingly, the RIBA Plan of Works uses a similar format to provide prompts for professionals aiming to integrate a DfMA approach in their projects. Lyon's framework for a DfMA-inspired design methodology for digitally fabricated components supports the need for a sequence of steps outlining the particular issues which must be considered or addressed at each phase. The model does not offer practical suggestions for design optimisation like the DfMA guidelines do, but rather suggests at what stages and in what order the various types of necessary production knowledge should be weaved into the design process. Lyon's flow chart (Figure 2) has obvious similarities to the process diagram outlined in Boothroyd, Dewhurst and Knight's seminal text *Product Design for Manufacture and Assembly* (Figure 1.)

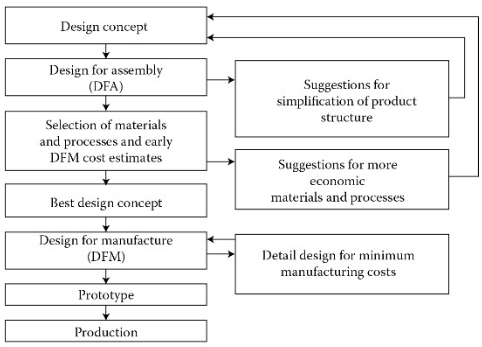

Figure 1. Boothroyd and Dewhurst's DfMA process flow, as found in *Product Design for Manufacture and Assembly.*

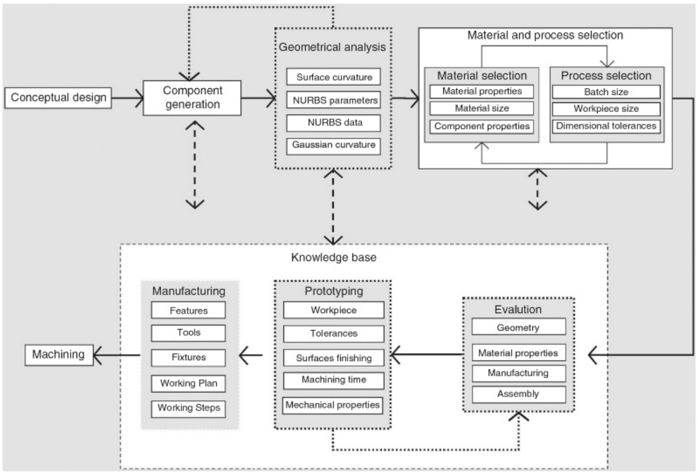

Figure 2. Lyon's framework for DfM for digitally fabricated components.

The Boothroyd Dewhurst DfMA method for quantitative evaluation facilitates comparison of various designs so that they might be optimised. The allocation of numerical values to various physical attributes enables designers to understand how each part of an assembly is contributing to the overall time and cost. While constructability aims to integrate construction knowledge throughout the entire life cycle of a building, it fails to provide a systematic method akin to DfMA. Some work has been done around developing optimisation methods appropriate for architectural design. Design Optioneering is a method for evaluating architectural design alternatives with "a DfMA perspective."[36] The method has been developed in response to the complexity of the problem of optimisation in architectural design resulting from the large number of disciplines and actors involved as well as the multiple varying objectives. The method is based on multi-objective optimisation which involves identifying several factors relevant to the cost of production, which are to be used as comparative criteria. Each design option is weighted with respect to each of the identified factors (which have been reparametrized between maximum and minimum values) and these are added up to give a total score. Giuda et al. give a façade design example in which the important parameters are shape, costs, number of modules and waste material. These are weighted according to the constructor's advice, which is based on "previous experience or expertise."[37] Giuda et al admit that this method for weighting the parameters opens itself up to subjectivity and potential lack of transparency.

In Singapore, the Construction Industry Development Board has attempted to tackle the same problem by developing a point score system to encourage implementation of buildability in new proposals based on three primary principles: simplicity, standardisation and integration.[38] Allocation of points is determined by the particular type of construction system used with a labour-saving index attached to each system. While this may be the only method for quantifiable evaluation of producibility in construction, the buildability score only describes the structure, walls and floors of a building at a systemic level, and has not been shown to reduce costs.[39] Furthermore, the scientific reliability of the method has been questioned[40] as, much like Giuda et al's method, lacks transparency around the source and validity of the metrics.

Outside of the field of buildability, other tools for quantitative evaluation of building design comparable to DfMA are being used as implementation strategies for sustainability measures. These point score systems, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), have been developed to optimise buildings for environmental performance, offering "a series of indicators or parameters to be maximized or minimized, in a hierarchic structure with a scoring system based on appropriately weighted credits."[41] These and others are becoming increasingly used in the industry, and while studies have deemed them only partially effective across all of their objectives (reducing waste, reducing energy and water use, and addressing indoor environmental quality and social issues), there is evidence to suggest that the tools have resulted in better performing buildings overall.[42] However, a critique of these tools which is important for the argument in this paper relates to the potential limitations in future innovation resulting from the reduction of complexity necessary to quantitatively evaluate building designs within the point scoring system.[43] Similarly, development of design principles based on current construction practice might limit new and innovative ways of building production that might be achieved through learning from adjacent industries.

Through field studies, the Fox, Marsh and Cockerham identify that development of new design rules for construction might be informed by existing DfMA principles[44] however the variety of interpretations and approaches to adapting DfMA for construction reveals that direct translation of the guidelines and method across industries is perhaps not possible. While the differences between the nature of construction and manufacturing have already been articulately pointed out in the literature[45], examining the peculiarities characteristic of the field of building design and production can offer insights to why this might be the case, and hint at a way forward.

One size doesn't fit all: Why DfMA is not entirely appropriate for building design and production

Production Context – The Role of Site

Within the field of industrialised construction, the production of a building involves several sites of manufacture and assembly along the supply chain. The scale of buildings and their intrinsic connection to place mean that they fall into the category of fixed-position manufacturing, a process in which assembly stations "move through the emerging wholes"[46] rather than the other way around. This is true of site production, as well as of some cases of building module production in a factory (for example, a volumetric building module in which various trades sequentially complete their work.) Ballard and Howell argue that these characteristics define building production as unique.[47]

At a high level, the design of buildings for manufacture and assembly involves decisions around the best way to divide the large conceptual whole into manageable and producible parts. The design of prefabricated building components and assemblies is very much dictated by their transportability to site, which means that size limits are determined by site location and the local transportation regulations. Where integration may be desirable to reduce part count, transportability introduces complications which can affect the assembly and installation efficiency of such a design.

Furthermore, the extension of building production processes beyond the controlled factory environment to that of the construction site invariably affects the assembly strategy. Issues such as varying ground conditions; physical access to the site and along the perimeter; environmental conditions such as weather; and local regulatory frameworks around safety (for example, regarding working from heights) inevitably affect the way that work is carried out. Site assembly, or 'installation' as it is referred to in *Product Design for Manufacturing and Assembly*[48], is therefore quite different to factory assembly. While the controlled nature of factory production can offer advantages such as reliability and assembly of parts at comfortable working heights, the immediacy of site assembly in the vicinity of the final location of the part can also have its benefits. A DfMA approach tailored to construction should recognise the value of each so that they might be leveraged for the efficiencies they might contribute respectively, whilst also negotiating their differing tolerance requirements.

Some definitions of DfMA within the context of building production pit assembly activities against construction processes,[49] as though they are diametrically opposing concepts. Interestingly, no definitions are usually offered for either, but assembly is assumed to be better than construction. Buildings are grounded structures, and as no two buildings exist on the same piece of ground, each building will interface with unique terrain, environmental conditions and social/cultural structures. The uncertainty of site introduces a degree of external variability with each new project. If we consider the condition of a traditional construction site, in which raw materials are delivered, manually processed and composited in a made-to-fit kind of way, we can think of construction activities as those which are able to mediate the variability (dimensional and otherwise) imposed by the nature of the construction site (in fact, construction workers often pride themselves on this problem-solving ability.) The production of a building on site will therefore inevitably involve a combination of assembly activities with those which more closely resemble construction. Perhaps a more productive approach to DfMA in this context might be to think about assembly and construction activities as two ends of a spectrum of building production which is tuned for optimised ratios on any given project.

Figure 3. The final site of production in a building project is defined by a unique combination of construction and assembly activities.

Product Scale

The data upon which DfMA has been developed refers to small or medium sized objects able to be lifted by a human or an automated feeding machine, as indicated by the size categories on the original DfMA worksheets. These contain upper size and weight categories of >15mm and >10lb (>4.5kg). Some building parts, such as windows, doors, taps, bath tubs and so on, fall into the category of DfMA applicable 'products,' and even some building modules, for example an integrated mechanical and plumbing unit, might exist on the smaller end of the scale spectrum. These assemblies and the factory processes required to produce them can perhaps be likened in type and scale to those involved in the manufacture of industrially produced objects such as cars. In this case, it would be fair to say that DfMA principles and methods likely apply as they would to any other industrially produced object.

However, as Boothroyd and Fairfield point out, "Obviously, one database of assembly times cannot be accurate for all situations."[50] Buildings are by nature large and are comprised of large parts and assemblies. This can affect several factors in their production including the acquisition and assembly/installation of parts as well as approaches towards tolerance design. The scale of parts and assemblies that make up buildings have a direct impact on the nature of the assembly strategy informing the lifting and installation logistics, in which manual labour is often supplemented with cranes and other mobile lifting machinery. Additionally, tolerance design must take into consideration issues such as deformation of large elements in lifting, transport or due to environmental factors such as humidity; differential settling across building storeys; and tolerance stack up. Similar scale-related tolerance issues have also been observed in the assembly of aeroplane parts[51], which are comparative in size to buildings. These factors influence the scalability of findings derived from the assembly of smaller objects, on which DfMA has been built.

Boothroyd, Dewhurst and Knight's seminal text acknowledges that "it is desirable, therefore, to have databases appropriate to those situations where the size of the product and production conditions differ significantly."[52] The DfMA method detailed in the 2011 edition of the publication provides a table for additional acquisition times to be used in calculations for those situations that call for larger and more flexible assembly stations within a factory, potentially even using lifting equipment. The upper limits of the data categories in this table are: >16ft (>4.88m) for the average distance to part location; >65ft (>19.81m) for the size of the largest part; and >30lbs (>13.6kg) for the weight of the part. The first two limit categories seem reasonable with respect to the assembly of building modules; however, it is likely that most building parts will weigh more than 13.6kg. A CLT floor module, for example, can weigh hundreds of kilograms, likely affecting the time taken to lift and move such a piece, particularly when considering the effect of momentum. It seems inappropriate to group such an item in the same category as a smaller part such as a ceramic toilet pan, which might weigh 40kg. This highlights the need for building production-specific data collection within the field as a way of quantifying the differences and informing design guidelines.

Design Objectives and Methods

While the definition of DfMA has been somewhat stretched in its translation to the construction industry, some of its objectives still appear to be aligned with those in manufacturing, namely a simplification of assembly processes, a reduction of assembly time and therefore ultimately a reduction of production cost. However in addition to this, increased quality and safety are often mentioned as additional drivers in the field of building production, which are more difficult to quantify. Quality in particular can be interpreted in many ways (technical quality, material quality, architectural quality[53]). Beyond the improvement in craftsmanship that can result from allowing work to occur in a controlled factory environment, quality refers to that intangible design value of both products and processes that inspires delight. Optimisation in this case becomes somewhat more complicated, yet important nonetheless. Maxwell's work on design-value in Industrialised House Building (IHB) investigates the current focus on technical considerations which prioritise production and method over phenomenon, arguing that "An IHB industry of the future will be able to balance hard and soft design-value" so that a "holistic, and responsive industry can emerge, no longer limited to niches that conform to limited contexts." [54]

The DfMA evaluation method involves a linearly iterative optimisation process based on already defined design details. Before DfMA can be applied, the product in question must be designed to a point where its formal attributes are known. Boothroyd, Dewhurst and Knight's seminal text acknowledges that there are indeed different kinds of design, and explicitly states that DfMA refers to the "detailing of the materials, shapes and tolerance of the individual parts of a product" rather than the aesthetic decisions that are made in the conceptual design phase; "the external shape of a car, or the colour, texture and shape of the casing of a can opener."[55]

Building design, like product design, involves different kinds of design at different stages of the process. In the conceptual design phase, formal, spatial, material and structural decisions are made in response to the geographical, programmatic, environmental, jurisdictional, cultural and historical attributes of the project.

However, unlike a car or a plane, which are to some degree predefined by their formal and functional typologies and limited expectation of customisation, the possible spectrum of design solutions for any given building is dauntingly broad. The 'designerly' approach[56] to arriving at an optimised solution in this particular context has been described as a non-linear, messy, divergent exploration and iteration of options. This design process involves defining and juggling hierarchical relationships between parts (tangible and intangible) and negotiating trade-offs based on a number of different priorities.[57] DfMA, on the other hand, can be described as a more scientific approach to design: linearly iterative, evaluative and convergent. Optimisation in this context is seen as a mathematical problem, a matter of inputs and outputs. One might draw similarities between this approach and the kinds of activities involved in the structural and construction detailing that occur in the later phases of building design development.

The nature and scale of the traditional building design timeline is such that key decisions which may affect the producibility of a design (those which might be most ripe for DfMA refinement) have likely been cemented by the time enough formal attributes have been established for detail design to occur. As identified in the literature, DfMA adapted to the building context would be most useful if it contained a temporal aspect which could inform decision making with various degrees of resolution. Furthermore, this paper proposes that such a method should be robust enough to propagate design decisions between the 'designerly' and 'scientific' modes of operating.

Conclusion: Towards a DfMA for an industrialised building context

Having highlighted the characteristics of building design and production which set it aside from the manufacturing context and the resulting discrepancies of DfMA definitions across industries, questions around the appropriate response might be raised. One could argue that for DfMA to make as much of a difference in construction as it did in manufacturing, we must move beyond accepting it as a broad philosophy. Perhaps instead, we should be focussing on strategies of implementation by asking questions such as: would buildability rules extracted from current construction best practice lend themselves to the kinds of designed solutions that might arise out of a manufacturing approach to the problems at hand? And how might we develop a successful operative framework for combining learnings from both?

Reflecting on the challenges of DfMA translation to an industrialised building context highlights the need for further investigation into multi-objective methodologies for guiding the design process and evaluating the designed outcomes with respect to production efficiency, cost, safety and quality. For this to occur, data collection on site is imperative. Current productivity assessment tools are likely inappropriate for obtaining the kind of data required to develop a DfMA-inspired method and guidelines which address the four points mentioned above. Furthermore, an approach to optimisation using the findings from site must be robust enough to be able to accommodate the varying kinds of design activities that occur from early concept development through to production. Finally, the analysis in this paper has pointed to aspects of building design and production that exceed the merely quantitative and numerical measures of the "optimal", gesturing instead towards the objective of making building design not only efficient, but inspiring delight in the makers and users of buildings alike.

Image Sources

Figure 1

Geoffrey Boothroyd, Peter Dewhurst and Winston A. Knight, *Product Design for Manufacture and Assembly*, 14, Figure 1.10

Figure 2

Eduardo Lyon, "Emergence and convergence of knowledge in building production: Knowledge-based design and digital manufacturing" in *Distributed Intelligence in Design*, ed. Tuba Kocatürk and Benachir Medjdoub (Blackwell Publishing Ltd., 2011), 93, Figure 6.14.

Figure 3

Author's own image.

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[17] Bogue, “Design for manufacture and assembly,” 113.
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[23] Sinclair et al., *RIBA Plan of Work 2013 Design for Manufacture and Assembly*, 6.
[24]Ibid., 18.
[25] Banks et al., “Enhancing high-rise residential construction through design for manufacture and assembly”, 164-175.
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[28] See Stephen Fox, Laurence Marsh and Graham Cockerham, “Design for manufacture: a strategy for successful application to buildings”, *Construction Management and Economics* 19*,* no. 5 (2001), 493-502.
[29] Ibid., 493-502.
[30] Definition from the Construction Industry Institute, Australia, as cited in the Preface of A. Griffith and A. C. Sidwell, *Constructability in Building Engineering Projects*, (Hampshire and London: Macmillan Press Ltd, 1995), vii.
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[32] See Robert Gerth , Albert Boqvist , Marcus Bjelkemyr and Bengt Lindberg, “Design for construction: utilizing production experiences in development”, *Construction Management and Economics* 31, no. 2 (2013), 135-150.
[33] Fox, Marsh and Cockerham, "Constructability Rules”, 695.
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[36] Giuda et al., “A BIM-based approach to façade cladding optimization”, 324-331.
[37] Ibid., 329.
[38] See Building and Construction Authority, *Code of Practice on Buildability*
[39] Abdulaziz M. Jarkas, “Effect of Buildability on Labor Productivity: A Practical Quantification Approach”, *Journal of Construction Engineering and Management* (2016), 1. accessed on September 15, 2019, DOI: 10.1061/(ASCE)CO.1943-7862.0001062
[40] Abdulaziz M. Jarkas, “Effect of Buildability on Labor Productivity”, 1.
[41] Giuda et al., “A BIM-based approach to façade cladding optimization”, 325.
[42] See Dominique Hes, “Effectiveness of ‘green’ building rating tools: a review of performance”, *International Journal of Environmental, Cultural, Economic and Social Sustainability* 3, no. 4 (2007), 143-152.
[43] Ibid., 150.
[44] See Fox, Marsh and Cockerham, "Constructability Rules”, 689-696.
[45] See David M. Gann, “Construction as a Manufacturing Process? Similarities and Differences between Industrialized Housing and Car Production in Japan,” *Construction Management and Economics* 14 (1996):

437–50. and Mathew Aitchison, "A House Is Not a Car (Yet)", *Journal of Architectural Education* 71, no. 1 (2017), 10-21,

[46] See Glenn Ballard and Greg Howell, "What kind of Production is Construction?", (paper presented at the 6th Annual Conference of the International Group for Lean Construction, Guarujá, Brazil, 1998)

[47] Ballard and Howell, "What kind of Production is Construction?"

[48] Boothroyd, Dewhurst and Knight, *Product Design for Manufacture and Assembly*, 117.

[49] On page 6 the RIBA Plan of Works DfMA Overlay suggests that "Designing for assembly considers how aspects of the design can be designed in a manner that minimises works on site and, in particular, in a way that avoids 'construction'." Similarly, on page 25 the Bryden Wood *Delivery Platforms for Government Assets* report proposes that one of the benefits of DfMA is that "Installation and assembly (as opposed to construction) sequences are more capable of precise execution."

[50] G. Boothroyd and M. C. Fairfield, "Assembly of Large Products", *Annals of the CIRP* 40, no. 1 (1991), 1.

[51] L.J. Hart-Smith, "Interface Control- The Secret to Making DfMA Succeed", *Proceedings of the First SAE Aerospace Manufacturing Technology Conference*, (Seattle: Society of Automotive Engineers Inc., 1997), 7-8.

[52] Boothroyd, Dewhurst and Knight, "Product Design for Manufacture and Assembly", 114.

[53] For a discussion of quality in the context of building design and production in the industrialised context, see Anne Beim, Jesper Nielsen and Kasper Sânchez Vibæk. *Three ways of assembling a house,* (Copenhagen: The Royal Danish Academy of Fine Arts School of Architecture Publishers, 2010).

[54] Maxwell explores the importance of design value in the field of Industrialised House Building in his thesis Duncan William Maxwell, *The Case for Design-Value in Industrialised House Building Platforms: Product to Ecosystem,* (PhD Diss., University of Sydney, 2018)

[55] Boothroyd, Dewhurst and Knight, "Product Design for Manufacture and Assembly", 6-7.

[56] See Nigel Cross, "Designerly Ways of Knowing: Design Discipline Versus Design Science", *Design Issue*s 17, no.3 (2006), 49-55.

[57] For an in-depth explanation of architectural design methods see Philip Plowright, *Revealing Architectural Design: Methods, Frameworks and Tools,* (New York: Routledge, 2014)