Industry Review

Design for Mass Customised Manufacturing and Assembly (DfMCMA): A New Framework for Mass Timber Construction

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The present paper outlines the erroneous use of Design for Manufacture and Assemble (DfMA) as a term and concept applied to Mass Timber Construction (MTC), in particular toward technologies such as Cross Laminated Timber (CLT). At the heart of the DfMA concept is a combination of standardised parts/components and standardised outputs. Indeed, the concept applies more to the Original Equipment Manufacturing (OEM) industry and largely stands at odds with the mass customised approach of MTC. A new concept called Design for Mass Customised Manufacture and Assembly (DfMCMA) provides a framework focusing on relevant platforms and the potential for gains in efficiencies through the use of platforms of stakeholders and technology. DfMCMA allows for a better understanding of the design, manufacture and assembly of MTC solutions bridging both off-site and on-site factors. The DfMCMA framework has applicability to the global MTC movement.

Keywords: *Design for Mass Customised Manufacture and Assembly, Cross Laminated Timber, Mass Timber Construction, Efficiencies, Technology*

Mass Timber Construction (MTC) is a new form of construction material and methodology whereby mass timber panels and other building elements are manufactured and shipped to a construction site for assembly delivering a building or other structure (Kremer & Symmons, 2015). MTC falls under an umbrella of technologies called 'prebuilt' or 'preconstruction', a method used for the primary purpose of securing on-site construction productivity gains, typically through the add-back of costs, time and labour savings within the preliminaries evaluation of a project. One such technology within the suite of these 'disruptive construction technologies' is Cross Laminated Timber (CLT). CLT is an excellent alternative to concrete and steel, or it may work in concert with traditional materials; hybrid construction. CLT is an engineered timber technology where timber boards are oriented perpendicular to adjacent layers, glued-bonded and pressed to form a solid rectangular billet, typically 16 metres by 3.5 metres. From these billets, construction elements and panels are cut typically forming the final structural elements of a building. The panels are cut using a Computer Numerical Cutting (CNC) machine. The panels are customised for the purposes of the project. Once completed the panels are sequenced for installation and shipped to the construction site for assembly.

The rapid rise of two concepts 'mass customised off-site manufacturing' and 'on-site construction' has resulted in a void of appropriate nomenclature, or terminology, in the current literature. Instead, existing terms are being modified and adopted where alternatives do not exist. For example, the concept of Design for Manufacture and Assemble (DfMA) is commonly used by those in the mass timber sector to describe a process of 'efficiencies gained through appropriate design of projects (the panelisation process) for both 'manufacturing' (an off-site processing plant) and for 'assembly' (on a construction site). The term DfMA is taken from Boothroyd and Dewhurst who developed the technology concept in late 1970's and early 1980's (DFMA, 2018). DfMA is the combination Design for Manufacturing (DfM) and Design for Assembly (DfA). However, the term's adoption by the mass timber construction industry, and companies that produce massive timber products, specifically products like CLT is erroneous.

According to Bogue (2012), few design engineers have detailed knowledge of all the different manufacturing and assembly platforms to truly create/undertake DfMA designs. As such, rarely are designs optimised to a point that gains in efficiencies are achieved and problems in the manufacturing process, or during the assembly method, avoided (Bogue, 2012). At the heart of the DfMA philosophy are several very important concepts centred around efficiencies. The primary idea concerns the standardisation of parts. DfM and DfA guidelines recommend using 'standardised' and 'off-the-shelf' rather than custom components. Further, not only is parts standardisation important for the concept, the removal of elements and a reduction in the number of overall parts assist in reducing time in manufacturing and improving efficiencies. What is also quite interesting about the types of products exemplified in DfMA case studies is that they are also standardised, for example a mobile phone (Apple or Samsung) or motors used in the assembly of cars or other equipment. They are not unique construction projects in which each output is often vastly different from the last one produced – often due to differences in on-site environments project conditions. Let's explore the concept of DfMA in more detail.

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DfMA Platforms

The platforms required to deliver a DfMA value proposition, or benefit, exist on two distinct levels. The first platform is the programs and design software that allow for assessment, design, and adjudication (exclusion and inclusion criteria) of parts and elements that constitute the individual units that when put together make 'the whole' [end] product (Constance, 1992). The second platform to consider are product-based platforms, such as a chassis on a car, or the circuit board in which transistors and capacitors are located. Typically, over time, product based platforms change, adapt and often improve in performance. The use of platforms is an important concept to understand in order to assess how best to get efficiencies out of standardised products that are manufactured and assembled.

Standardisation of Components

According to DfMA proponents, standardization (and not customisation) is one of the keys to success (Bogue, 2012). Standardisation within the context of the present paper refers to the manufacturing process and should not be confused with product standards, such as compliance to European Technical Assessments (ETA), Australian or American Standards. Standardisation provides 'certainty' to manufactures of standardised products, specifically in the domains of quality control and quality assurance. Certainty extends to the availability of parts and to the performance of the components that constitute the end product, providing reliability through repeated manufacture and assembly over time. The concept of reliability extends to performance of the product in the hands of an end user ensuring that the product functions as intended. The standardisation of parts also allows for specific tooling for machines that assemble standardised products. A company's investment in such equipment and tooling is contingent on control over 'the process' ensuring equipment performs as expected achieving expected outputs/efficiencies. Indeed, investment calculations, Return On Investment (ROI) — and assessments of capital expenditure — function extremely well when quantifying the outputs of a standardised processing from a set-fast machine. It is more difficult to quantify the value of a machine that does not have constant standardised inputs and outputs.

Standardisation of Outputs

Much like the standardisation of components that constitute the entire finished product, having a standardised product ensures certainty in forecasting sales demand, performance reliability and easy access to replacement parts/units for reparation under warranty. Standardisation makes it easy for companies to build stock of specific items whilst being agile in production shifts, given the seasonality of demands for products in-market. Standardisation also allows for a common platform upon which new models can be developed as features are added, or morphed, into the next 'on-trend' item. Given the aforementioned commentary, how does the concept of DfMA relate, or not, to MTC?

Platforms and Mass Timber Construction

The adoption of 'platforms' in construction is not new. There are several types of platform, including digital platforms (Building Information Modelling; BIM) and physical platforms (including Subfloors solutions, Heavy-framework and Structural systems i.e. Beam and Post etc.). Platforms serve a useful purpose and are associated with a common language that allows for efficient communication about systems and solutions on projects. Digital platforms, for example BIM, allow for collaboration between users along the supply chain and offer the opportunity to work on a model in real time [in the cloud]. Often such collaboration results in providing guidance and information about changes one stakeholder makes to the entire team on the project. Communication in this way is efficient and timely allowing teams to develop plans for a project relatively quickly, and thus more efficiently.

Physical platforms allow for a common terminology in communication about the area of the building stakeholders are discussing, for example the basement or lift shaft. Physical platforms also allow for the development of production solutions by those companies that manufacture products including glass curtain wall systems, or subfloor bearer and joist systems etc. Physical platforms also allow for innovation to occur, for example the development of timber floor cassettes. Timber floor cassettes are seen as a natural progression from the assembly of individual labour-intensive components in-situ (on-site), such as bearer and joist systems. Timber cassettes are large-area cartridges/modules or prebuilt sections of floor systems providing improved on-site efficacies through labour and time saving because you can install larger sections of flooring in less time. Not to mention, the cassettes are produced in a controlled factory environment affording a level of quality assurance and control above that which can be achieved on a construction site.

Standardisation and Mass Timber Construction

We have seen that the original DfMA concept has several factors that when working in concert will drive improvements in the manufacturing process — through cost reduction, productivity gains, process efficiencies etc. DfMA includes the notion of standardisation, both of parts and units of output. Whilst it is recognised the timber feedstock used in the creation of MTC products will have specific dimensional thickness and certain other consistent qualities (Modulus of Elasticity or MoE, species of timber, treatment etc.), the term standardisation is not often associated with the mass customised panels and other elements. Let's look at an example. By their very nature construction projects are typically unique in design/architecture. Two different architectural firms working on individual concepts for the same land development site will invariably produce very different proposals as part of their pitch for the work to developers. Indeed, one could argue that individuals who identify as architects will often strive for 'difference in design' not commonality, or homogeneity. Therefore, before we examine DfMA in the context of MTC, we have already found a significant divergence between the desired customised/non-standard outputs found within a construction project and the desired outputs (products) from a company like Apple or Sony (smartphones) that align more closely to the DfMA original concept.

Following this logic further, as part of developing a unique and often bespoke construction project, inevitably the components regardless of the material they may be manufactured from will also likely be bespoke or quasi-customised — requiring slight alteration. Some might argue such is the nature of creating a modern architectural building. Yet, it could be argued that a modern housing estate anywhere in the world may have a set number of 'house types', which share the same footprint or series of components that are identical. However, the numbers in which these housing-type replicates are produced, the number of standard units/components (the houses) required, may not be of a significant magnitude/volume/quantity to warrant dedicated resources for an ever-evolving or continuous standardisation improvement process to gain increased efficiencies overtime. Importantly, the number of units concerned with the DfMA concept and the influence of technology in manufacturing plants are in the millions, not the thousands or hundreds. In the next section we extend our review of the aforementioned concepts further.

Why DfMA does not work for MTC?

MTC projects typically begin as a 3D model. The client, through an intermediary such as an architect or building designer, will provide the design intent, which shall be modelled/drawn. Typically, CLT manufactures will take this model and 'panelise' the project. Panelisation is the process in which a Computer Aided Design (CAD) operator will build-up the structure of the proposed project using digital CLT panels and elements. The panelisation practice establishes the relationship between each panel in the overall structure of the project, and represents the step immediately prior to the shop drawing process used to manufacture the product/s. Each panel and element that is cut constitutes a portion of the overall structure, often many panels will not be replicated twice. At best a CAD operator might be able to replicate some walls or floors, however even those elements might require unique modifications— due to service and other penetrations design into panels.

In many cases the development of a panelised model can be optimised by altering the orientation of the panels in the model, or by attempting to make the largest possible panels for the project to save on crane lifts on-site. However, a number of other factors, such as road, rail or sea transportation restrictions and limitations, interfere with what might be possible from a delivery efficiencies perspective. Importantly, in every project the tension between 'design and engineering', 'efficient manufacturing', 'proficient construction or assembly' all whilst meeting the client's expectations for the project will invariably create conflict amongst those arguing for 'the best way to deliver the project'.

Considerations associated with on-site assembly offer a unique complex to any project, specifically relating to the exact and precise sequencing of deliveries and placement of panels/building elements during assembly. Each panel modelled within the virtual environment is provided a unique identifier to ensure its place in the construction sequence. It seems quite straightforward, a contractor on-site need merely follow the sequence and erect the building. However, often the construction sequence and the delivery of panels to site do not highly correlate, thus creating a need to stage panels on-site and [re]shuffle the construction sequence, which is not very efficient. Non-standardised components, non-standardised projects and now the potential for a different method of installing each panel on each project. These are all departures from the highly standardised DfMA concept outlined earlier? A new concept is needed.

Design for Mass Customised Manufacture and Assembly (DfMCMA)

If we accept that MTC involves a high degree of non-standardised but highly customised panels and elements uniquely produced, sequenced and assembled for a structure in a project then applying DfMA is not the appropriate. The proposed replacement term is Design for Mass Customised Manufacture and Assembly (DfMCMA). The DfMCMA concept includes the following elements. Firstly, DfMCMA includes platforms. Indeed digital platforms (software, IP generation etc.) as well as stakeholder platforms (formation of a consortia, architect, engineer, builder etc.) who support the project throughput its lifecycle. Secondly, DfMCMA is all about efficient mass customisation. The delivery of any project must also be efficiently designed, manufactured and assembled on-site. Each of these are core benefits from using prebuild panelised technologies like CLT and GluLam. Each of these shall be discussed in further detail next.

DfMCMA Digital Platforms

With the rise of BIM, and other software technologies related to MTC (CAD and CAM for example), there is a common aim in achieving a seamless transition between designing in BIM, or other 3D environments, using a suite of digital element libraries to enable designers to produce panelised building structures. In the near future, designers, architects and engineers etc. will have the ability to design in BIM and have that 'intelligence' translate through several layers of review (by the project consortia) and be sent directly to a manufacturer. The manufacturer can then quite easily translate the panelised drawings into files, which are sent to the CNC for processing. The CNC operator may add or remove additional lines of operational code instructing the CNC to choose tools designating where and with what tool to manufacture CLT panels. The panels and elements are then cut from the larger billet slab.

A significant opportunity for 'efficiency gains' contained within the DfMCMA concept is the ability to move from BIM and other 3D software directly to CNC fabrication. Ultimately removing the shop drawings and CNC operational coding processes. The process as outlined also provides an opportunity to create virtual prototypes and move directly to physical mock-ups very quickly. The process of transforming 3D digital models into tangible reproductions is termed Digital Fabrication (Bickel, Cignoni, Malomo, & Pietroni, 2018). Digital fabrication offers the most significant efficiency gain in the production of a mass customised product, such as CLT. Importantly, it is know that several known software companies are currently in Beta trials to export BTL and BVX files (a type of Extensible Markup Language, XML, file) from the CAD program straight to the CNC.

DfMCMA Stakeholder Platforms

In the new era of 'prebuild' and 'preconstruction' the collaboration of a broad spectrum of stakeholders involved in a project is vital. Typically, the architect, engineers, developer, builder/constructor and manufacturer are all required to support a prebuild project. The novelty of the inclusion of the client adds another dimension to the group, in that clarity about the project can be clearly articulated at meetings by the client — ensuring integrity of the design intent. The use of a software, such as BIM, in conjunction with the stakeholder platform ensures that the project can be clearly designed through a collaborative process and that the 'customised' project is executed with greater efficiency and precision. Indeed, a project containing a consortia of stakeholders is not an uncommon phenomenon in today's construction world, however the timing of the engagement of the various stakeholders is the key ingredient. The early selection of the consortia—through an Early Engagement Process (EEP), such as Early Contractor/Consultant Involvement (ECI) or the like—is where gains are found in DfMCMA stakeholder platform. If a consortia can agree upfront details of the project in a collaborative forum, the ineffectiveness of the more traditional serial-processing approach in traditional construction is reduced/eliminated.

As an advanced form of collaborative platform, the use of Blockchain technologies (Morris, 2016) can provide another dimension to collaborating with multiple stakeholders whom, traditionally, have adversarial and distrusting relationships with each other. Blockchain can be viewed as an 'objective log' of stakeholder decisions thus making parties accountable for decisions in design and delivery of projects. Whilst there is considerable propaganda about the technologies applications at present, such a technology could be commonplace in the construction industry in years to come. Indeed, a key component within any stakeholder platform is the commitment to 'trust' and 'values' of the group, which are set aside here and form the basis of an entirely different paper altogether.

DfMCMA Mass Customised Manufacturing Efficiencies

Unlike the traditional DfMA approach, which seeks to standardise and reduce parts/components, DfMCMA allows for the creation of a unique series of panels and elements for an individual project. It might seem counterintuitive that mass customisation can result in efficiencies in manufacturing, and yet there are several important efficiency gains. The first involves the efficient design of panels relative to the design of architecture, building physics and engineering (structural, acoustics and fire) requirements. The second is the efficient use of raw materials. For example the efficient use of the whole billet (a CLT slab measuring roughly 16 metres by 3.5 metres) from which the panels are cut—a process called nesting, which is akin to a baker rolling out biscuit dough and cutting cookies using shape-cutter, optimising the placement of geometric shapes for cutting on the CNC. Finally, there is efficiencies to be gained in assembling product (panels and other elements) manufactured off-site and assembled on-site using a carefully planned/coordinated sequence of lifting. Whilst the DfMA concepts implies the accumulation and assembly of parts in the factory environment, the DfMCMA concept bridges both the off-site and on-site aspects of the MTC. Let's dive a little deeper into each of these concepts.

DfMCMA Efficient Panel Design

In a typical construction project there are many competing demands that govern the overall construction method, material selection and finished aesthetic. In the case of MTC, and in particular products like CLT, the main dynamics include engineering the right solution in terms of structural design, fire and acoustics, then consideration can be given to aesthetics. In many cases, the use of CLT as both a structural product as well as an aesthetic finished panel makes good economic sense. The 'levers of efficiency' within the DfMCMA concept for a product like CLT relate to the type of material selected, the thickness of panels, the spanning capacity and the load properties. Whilst these panels are not standardised, they are mass customised, the ability to find commonalities between material types, lay-up of feedstock materials, thicknesses and spanning/loading capacities 'with in' the project allows for a relative degree of efficient design. Panel efficiencies, in this sense, must be considered as part of a single project only, not a comparison between different projects because we know the majority of projects are unique.

DfMCMA Efficient Nesting

Relative to the design and scope of the project, once the panelisation is completed the geometric shapes, or the panels, must be optimised for cutting from the billet. There is software that optimises panel nesting, however anecdotally human intervention for nesting panels seems to still be the preferred option. Nesting is a combination of logistics, production planning and art! In any project there are likely to be an assortment of panel shapes and sizes to be cut from billets. Unlike the DfMA concept, a MTC manufacturer cannot simply just 'remove or reduce' these parts/elements to make efficient use of the CNC time. However, what can be done is the arrangement of panels across multiple billets to ensure the efficient cutting. The 'art' is also about understanding the way a particular project comes together — how the constituent parts form a whole, the sequence of construction, the order of loading, the lifting sequence on-site. In addition, knowing the limitations and various tooling capabilities of the particular CNC machine used in production is vital. Indeed, it might even be wise to have several CNC's with different capabilities, for example, a large format cutting CNC and another CNC that provides a more architectural and finite detail output.

DfMCMA Efficient Assembly

The primary efficiency levels for MTC are not only in the manufacturing plant but also on the construction site. The DfMA concept relates to a single environment, the manufacturing plant, and does not include an alternate site for efficiencies, such as a construction site. The DfMCMA approach focuses on the interplay between production/manufacturing efficiencies and assembly/erection efficiencies of the structure on-site. In order to provide the assembly efficiencies, the use of the CAD programs to determine a virtual construction sequence sets forth a planned approach to the assembly of panels on-site before the panels arrive. As part of the production process, panels are produced and labeled in accordance with the preordained assembly sequence. Installers and builders need simply locate the right panel, crane it into place and fix down, prop or tie-off until the next panel arrives. Such a method of construction removes a considerable amount of time and labour compared to more traditional forms of construction, such as wet-pour steel reinforced concrete.

Future Research

Future research might like to explore the concept of cost efficiencies of DfMCMA in a comparative study with a more traditional approach to manufacturing and assembling an identical project. Of significant interest would be the location/place of the DfMCMA concept amongst comparative manufacturing concepts. In addition, given the considerable focus on efficiencies gained on-site at present, the DfMCMA concept aims to reduce the additional time in design associated with MTC. A further study might like to explore the efficiencies gained by the adoption of digital fabrication solutions and calculate the savings in the MTC design stage thus increasing the overall total time for a project both off-site and on-site.

In conclusion, reframing the term DfMA to DfMCMA and focusing on the mass customisation of panels or elements in MTC provides a much improved framework for understanding the process of designing, manufacturing and assembling projects using technologies such as CLT and GluLam. A common element that both DfMA and DfMCMA concepts share is the use of 'platforms'. Both concepts rely on the use of digital and other platforms for the benefits of each to be realised. It is argued that the DfMCMA concept replaces the term DfMA because using such a concept in the context of MTC is erroneous. Particularly since DfMA refers to standardisation and reduction of parts in addition to focusing on efficiencies in the manufacturing plant only. DfMCMA seeks similar end goals to DfMA, the improvement of efficiencies, however DfMCMA takes into account the various complexities associated with a mass customised solution that is tailored to each unique project located anywhere around the globe.

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