Accelerating the adoption of DFMA for the Australian prefab building industry

Project Funding Agent:
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Design for Manufacture and Assembly

The term Design for Manufacture and Assembly, or DFMA, has been adopted by the prefabricated construction industry in recent years to describe an integrated and iterative process to accommodate improved design, manufacturing and construction assembly (Kremer, 2018). The adoption of the terms is often used to explain a rather complex process that has its origins back in the 1970s and 1980s by Boothroyd and Dewhurst.

History

Boothroyd and Dewhurst developed two concepts, namely Design for Manufacture (DfM) and Design for Assembly (DfA) when combined the evolution of the two processes aim to simplify the design of an object. An assessment of the individual components that constitute the object and reduce the number of elements within to improve the assemblage of the final product/outcome. Further details can be found in Figure 1.

Design for Manufacture (DfM)

- Apply the best design processes
- Explore the best material types for the application
- Understand the specification and tolerances of the object
- Optimise the process through and iterative, or looping, review

Design for Assembly (DfA)

- Reduce and minimise the number of parts in the object
- Consider the assembly/construction process
- Optimise to the maximum efficiency

Figure 1 Design for Manufacture (DfM) and Design for Assembly (DfA) Concept

At the core of the concept DfM and DfA the aim is to achieve lower costs for material (through standardising and reducing parts) and to become more efficient at assembly/construction to save time. Typically, the use of the combined concept, DFMA has been applied to industrial design/engineering and manufacturing environment, for example, car components, as Figure 2 depicts.

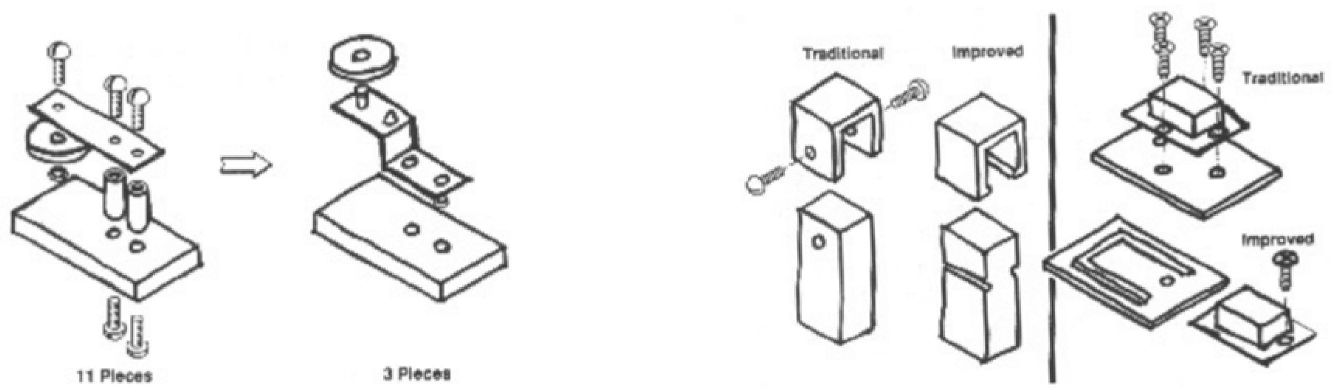

Figure 2 Parts reduction and assembly support following DFMA process (AT & T, 1993)

The redesign of the components and the reduction of parts, in the case of Figure 2 the number of screws, simply through that application of the DFMA process can have a significant impact on the way a part, or series of parts can be produced and assembled. In addition, the removal of parts, can have an impact on the auxiliary resources, for example, the reduction of warehousing, reduced labour and administration time in purchasing the items, lower inventory holds and more liquid cash to fund activities.

Benefits of DFMA

- The benefits of DFMA are clear, if applied correctly, you can expect to achieve the following:
- The reduction in the number of parts – both the types and quantity
- The assembly time is increased as the optimisation of the process is often much faster
- You can achieve improved lead-times including support for the 'just-in-time' manufacturing approach
- Associated costs (packaging, freight/logistics) are reduced

- Uptime in the production process is improved through the completion of more units in the same time due to the productivity and efficiency gains
- The overall costs of materials can be reduced, through reduction and potentially replacement/substitution
- The quality of the outputs in significantly improved due because of the controls around standardisation of parts, components and outputs

Example from the Digital Equipment Corporation

The example below was the results of the application of DFMA principles when re-designing a mouse. Some of the improvements realised were:
- The number of parts used was reduced by 50%.
- The number of assembly steps was reduced by 33%.
- The amount of time required for assembly was reduced by 53%.
- The volume of material required was reduced by 47%.
- The cost of packaging was reduced by 41%.

The outcomes not only provided the savings as outlined above, however, the project also resulted in the production of the mouse in approximately half the average time under the previous manufacturing approach. Of noteworthiness, the application of the DFMA concept

DFMA and the Prefabricated Construction Sector

In the prefabricated construction sector, DFMA can be applied to three core streams of work. The streams of work will have varying degrees in which they are completed either off-site or on-site. The three streams include:

1. The Structural Stream – including prefabricated 2-Dimensional (2D) and 3-Dimensional (3D) structural systems, for example, panelised construction includes prefabricated concrete (precast) or Cross Laminated Timber (CLT) or Panelised Wall and Floors Systems (PWFS).
2. The Cladding/Finishing Stream – including the completion of internal lining and surface finishing applications/ treatment and the use of cladding/facade solutions. The inclusion here of bathroom pods and other volumetric units – with varying degrees of finishing – are also included in this stream.
3. The Mechanical, Electrical and Plumbing (MEP) Stream – including pre-wiring/connection of systems for air conditioning, waste, lighting, power etc. through to the use of MEP modules and skids, the prefabrication of services trays/catwalks and then the including of MEP in 3D volumetric units.

Within the streams is the continuum of integration. The manufacture of individual components off-site requires significantly more assembly on-site. Whilst highly integrated assemblies, often 3D volumetric solutions, require less on-site assembly, yet carry other disadvantages, for example, they are more difficult to transport, there is a greater degree of risk damage in transit and construction.

The challenge now becomes a question of balance. The balance between off and on-site assembly construction and the level of integration. The following figure outlines the relative position of some common technology types with respect to the balance discussed here.

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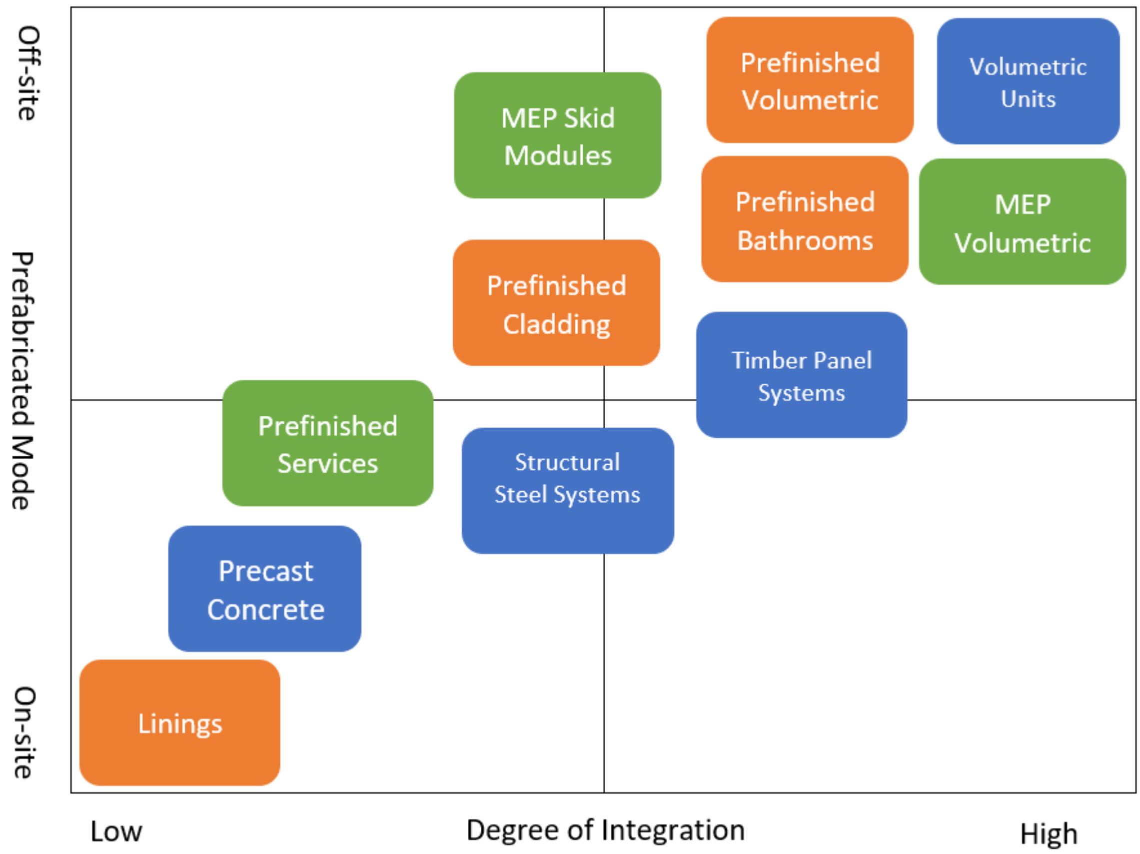

Legend: Blue = Structural Stream, Orange = Cladding/Finishing and Green = MEP Stream

Figure 3 The relative position of technology streams by construction mode and level of integration

The calibration factor in Figure 3 is typically 'labour on-site'. The reduction in labour on-site is critical for prefabrication and exists in the DfA aspect or component of the DFMA approach. Each technology approach gives a different utility to actors employing a prefabricated construction philosophy.

DFMA is an Iterative Process

The process that supports DFMA can only be described as iterative. In that, the evolution from design to review for both the 'design for assembly' component and the 'design for assembly' or construction phase, must go through several cycles, in order to refine and further define the project (Kremer, 2018).

The goal of the DFMA process in a prefabricated construction sense is to reduce assembly time, identify errors and problems whilst in the design phase, remove any waste from the process and drive a quality that is not offered by more traditional approaches to construction. The following value benefits form part of the process.

1. Identifying value through DFMA
2. Mapping the value stream
3. Create a flow for the work (manufacturing and assembly)
4. Establish a 'pull system' to drive the project through to completion ahead of time
5. Pursue the best possible outcomes for the value chain

Each of these important benefits from the process of DFMA as applied to the prefabrication construction sector will be discussed briefly next.

Identifying Value through DFMA

Each construction project is different. The factors underlying the difference in the ways the projects differ are contingent upon some of the following, this is not an exhaustive list.

1. The class of the project. Projects will sit in a classification of the construction typologies each with a specific focus on the ultimate use of the building and the type of construction project, i.e., Class 1 Domestic or Residential (National Construction Code of Australia, 2021).
2. The geography or place – where the building is located, i.e., urban, remote, rural etc. – of the project will have a bearing on the type of construction methodology.
3. The architectural design and intent, in other words, the aesthetic and form and function of the project.

Determining the approach, prefabrication or not, is a matter of assessing the suitability of the project. There are some basic guidelines for assessing if the use of prefabrication (and thereby applying DFMA) is applicable.

1. Is the project suitable for 2D or 3D prefabrication technologies?
2. Are the building elements (i.e., panels or volumetric units) able to be produced off-site and consist of a 'kit of parts' or building modules?
3. Are the building elements replicable and repeatable?
4. Can the components be produced using efficient manufacturing, i.e. advance equipment processing (automation)
5. Does the process of manufacturing involve the use of computer systems for design and machine operation?

The problem, challenges, barriers and opportunities for Designing for Manufacture and Assembly

The problem

The issue isn't as much with the technology availability as with its implementation in the prefabricated construction sector. The construction sector is dominated by small and medium-sized companies. It's not sufficient to modernize just one aspect of the construction industry as the modernized entity often finds itself in the queue behind a bottleneck that is yet to be resolved. The solution that prefabricated construction proposes is that of decreasing the dependence on multiple independent slow-moving gears and bringing them together under one roof. The extent to which this can be implemented is governed by the extent of standardization that can be achieved in a building construction project. Robotic hardware and software architecture is getting better every passing day and there are always newer technologies available for companies to start with. This poses a challenge of standardization even amongst those who have adopted a modern manufacturing technology. The factor of cost and the economy of scale is yet another challenge that has proven to be a stubborn barrier in the prefabricated construction sector for decades.

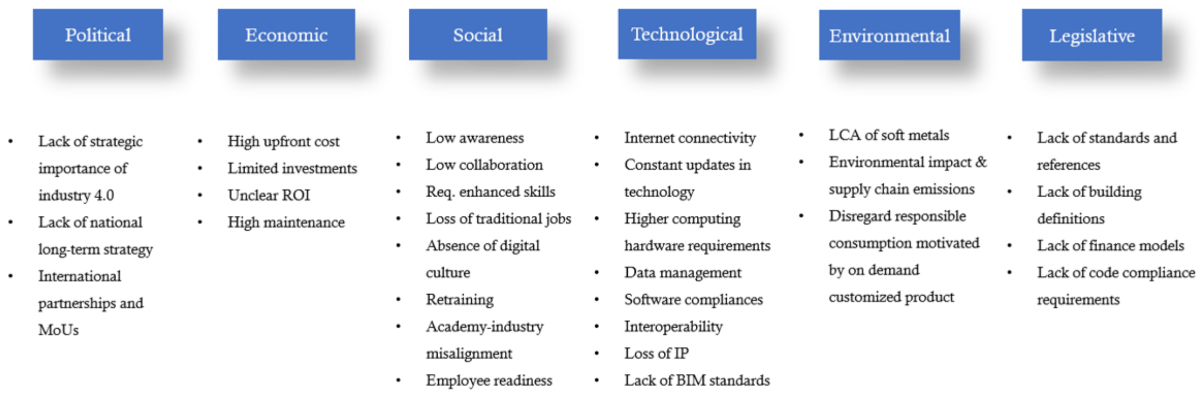

Figure 4 Typical barriers to DFMA in the Australian construction sector

Political and Legislative

Legislative changes are the direct consequences of political will for a paradigm shift in construction, a sector that is one of the slowest to adapt. Construction in Australia provided direct employment to 1.18 million Australians, contributed $360 bn in revenue amounting to 9% of Australia's GDP as of 2020 (AISC, 2020). The sector is largely seen as change and risk-averse and hence any legislative change that has the potential to disrupt the status quo finds itself difficult to manifest. Political agenda would need to set courses for prefab friendly legislation that could then act as sources of accreditation and process certifications for prefab industry partners.

Australian Building Codes Board (ABCB) produced National Construction Code (NCC) is a standard compliance document that regulates the development in the construction sector. Manufactured homes and prefab building products could be integrated into NCC that would mitigate the quality variance and boost compliance. Australian Standards would need to be extended to provide structural compliance requirements to various prefabricated buildings and products. Various state-level government bodies such as Departments of Planning, home warranty and insurance schemes would need to account for the rising prefabricated building market and suitably amend the existing provisions to include them. Government organizations, NGOs, industry, and academia would need to collaborate closely, and the collaboration would need to increase significantly to drive the change forward with respect to DFM and DFA in the prefab construction industry through innovation hubs, Testlabs and growth centres (ADIESR, 2020).

Economic

Economic impetus is crucial in the development of any industry. Financial backup is one of the most important driving factors amongst others listed in Figure 5 for prefab/off-site manufacturing (Bertram, Mischke, Ribeirinho and Strube, 2021). Unfortunately, the factors aren't independent and are required to be addressed parallelly at once, to drive the change forward. The government could nevertheless ensure that an adequate regulatory framework is in place for the development of OSM using DFMA. The process certification and quality accreditation brought through such a regulatory framework could then pave way for financial lenders to invest more freely into DFMA led OSM that would accelerate the growth (Feutz, 2021).

The government plays an important role not only as a political driver but also as an economic driver. Government can provide the necessary push for the industry players to move to modern methods of construction derived from DFMA. Permanent modular school buildings program by Victorian School Building Authority (VSBA), public housing through movable units by Housing Victoria, prefabricated quarantine accommodation tender issued by Victorian State Government are some of the examples of the State government's direct investment push to prefab industry in recent times.

The larger chunk of invested capital comes through private investments by direct consumers, banks and large financial institutions (Lin, T, 2021). DFMA led OSM finds itself struggling to attract investor confidence in the current Australian construction investment sector. This is due to multiple reasons ranging from end-product quality, business viability, design flexibility, regulatory compliances and provisions, and general risk aversion of traditional banking institutions. As shown in Figure 5, consolidated and continuous demand volumes is a critical factor for DFMA led prefabricated construction uptake.

Consumer perception of the product quality and design coupled with price competitiveness helps strengthen the demand pipeline. Current DFMA techniques in manufactured housing would need to be tailored to attend to this aspect for it to be more desirable.

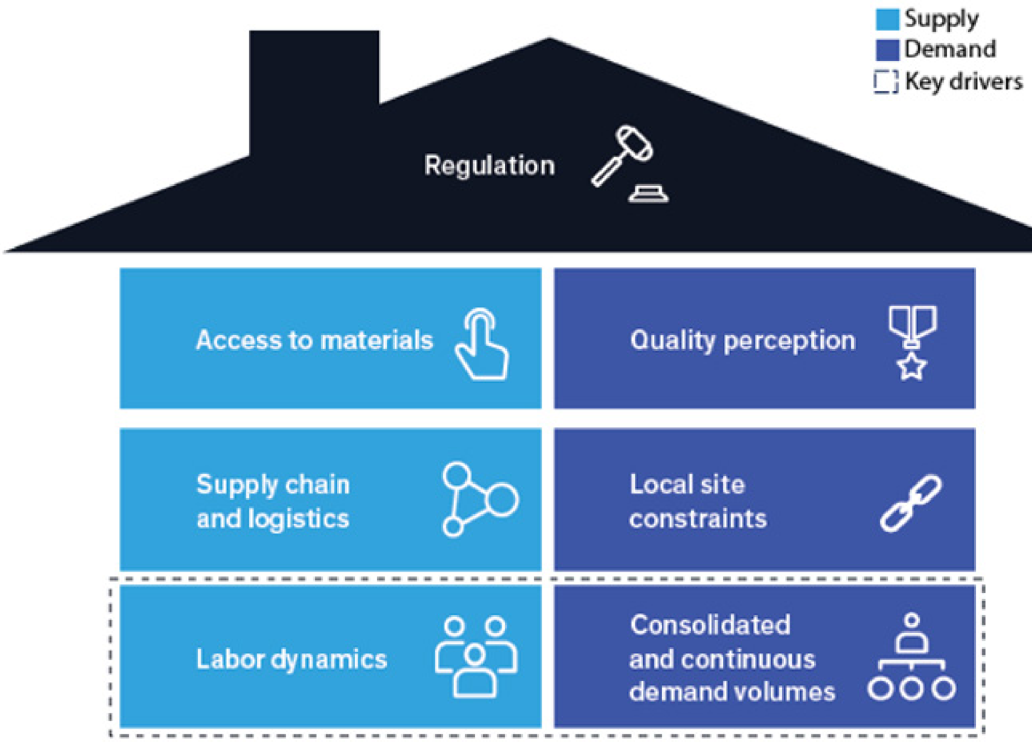

Figure 5 Driving factors for prefab industry uptake in the construction industry. Source: McKinsey and Co.

Technological

The construction sector is one of the slowest adopters of new technology as pointed out by McKinsey and Co. (See Figure 6) (Blackburn, S., 2017). Technological advancements in design, manufacturing, materials, monitoring and management form the backbone of DFMA philosophy. BIM, robotics and automation in the assembly line is proposed to facilitate the rapid production of prefabricated housing products. Advances in sensors, computing software and hardware, machine learning and AI, cloud computing, blockchain and so on have significantly increased the production methodologies across manufacturing sectors. These technologies are being introduced to prefabricated construction through DFMA principles. The implementation of these technologies is capital intensive and requires personnel with in-depth technical understanding. Since a large portion of the construction industry is essentially dominated by SMEs, the adaption of high-end technology poses a great deal of financial and technical challenges.

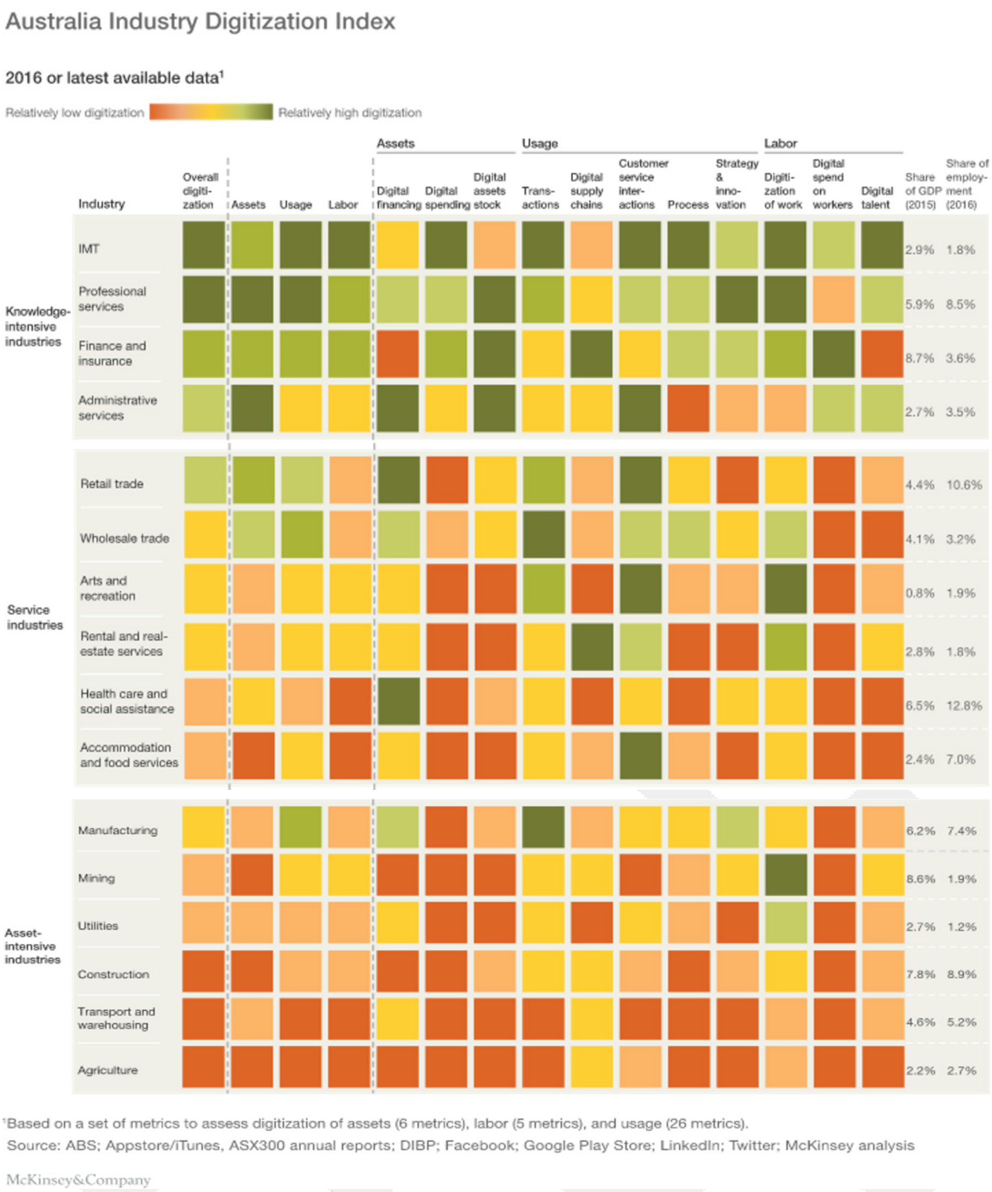

Figure 6 Construction sector placement in readiness for technology adaption

On the other side, the technology changes rapidly leaving behind those who do not have sufficient resources to upgrade the hardware and software. The suite of technologies bundled under the umbrella term 'Industry 4.0' is directed towards encapsulating required technologies for advanced manufacturing. The adoption of industry 4.0 techniques into construction would enable SMEs and large firms to implement DFMA with greater success. Australia Germany Advisory Group was formed in 2014 with the view that the Australian manufacturing sector would benefit from German Industry 4.0 software architecture and hardware advancements (AGAG, 2015). State government initiatives such as 'Victorian Digital Asset Strategy (VDAS) is aimed at moving towards digital twin models for the infrastructure assets. Digital twin technology can be harnessed to optimise OSM through DFMA effectively if a large number of industry players adapt to its usage.

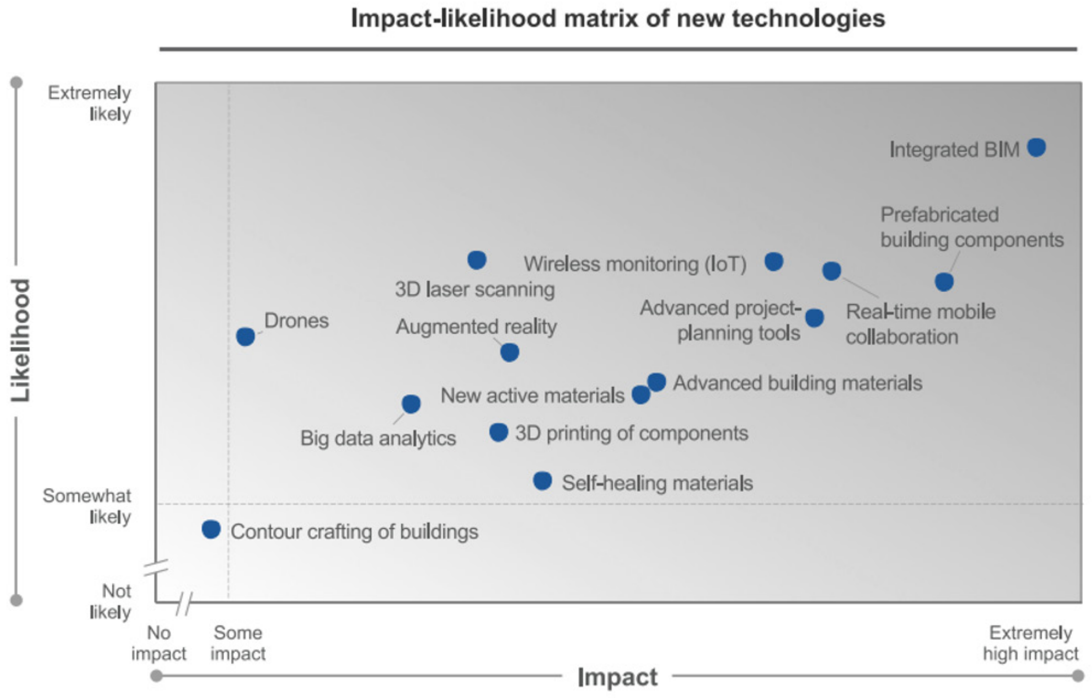

Figure 7 Modern methods in construction through DFMA and its impact (World Economic Forum, 2016)

Social

Industry awareness and perception of new technologies rank low in Australia which makes the adoption of advanced manufacturing principles difficult. The collaboration between academia and industry could be strengthened to provide ease of access in uncharted technological territories. Robotics and automation are largely perceived as a threat by the established labour unions associated with large scale job losses and substantive re-training requirements. The absence of easily available skills and training programs for advanced manufacturing technologies creates further roadblocks to those who are aware and are willing to re-train themselves.

The cultural acceptance of OSM buildings is yet another hurdle in the large-scale uptake of OSM methodology. Despite a range of benefits claimed by OSM, not many have passed the test of time as yet for its natural acceptance into the larger consumer market. Even though the OSM building technology is not a new phenomenon the older versions of the prefabricated houses resembled those that were built as rehabilitation shelters for returning soldiers of war post-WWII era. The stigma attached to the box type temporary houses propagates through decades and still presents as a challenge today. The architects and engineers would need to understand the socio-economic and cultural barriers that exist in the adoption of OSM houses and would need to tailor the DFMA protocols accordingly.

Opportunities:

DFMA brings tremendous opportunities for off-site manufacturing of buildings.

- Prefabricated construction currently occupies only 3-5% of the total market share in Australia.
- Cement in the construction industry is responsible for around 6% of direct carbon emissions around the world. The construction industry in Australia is responsible for about 30% of carbon emissions (Sattary, S., 2016). DFMA led OSM can significantly reduce the carbon footprint by reducing embodied carbon as well as operational energy during the lifecycle.
- It can provide mass and affordable housing for all.
- DFMA technology fuelled with modern methods of construction would significantly improve industry efficiency.
- Can provide an environment friendly and sustainable building product.
- Significant improvements in worker health and safety would be realized in offsite construction practices
- Increased participation from women could be seen as the working environment would be less onerous and safer.
- DFMA led Off-site manufacturing would reduce waste during construction.
- It would reduce transportation requirements to the already congested construction site in the city
- Lesser transport vehicles to the construction site would mean much lesser disturbance to the locality in terms of traffic disruptions, construction noise and dust.

A review of initiatives in key overseas jurisdictions

United Kingdom:

- As a part of the National Infrastructure and Construction Pipeline 2018, the government committed to increasing the use of prefabrication and offsite methods on public projects.
- At least 5 central government departments to leverage their spending power to support the modernisation of the offsite construction sector
- Industry-wide consultations are underway for a platform approach to DFMA
- National Housing Building Council (NHBC) launched an online hub for modern methods in construction (MMC) to build confidence, provide procurement assurance, provide continuous improvement guide and certify investible and tradeable assets
- Autumn budget 2017 set aside £34m to develop construction skills, £204m for innovation in construction including re-training of the construction force (Langston, C, 2021)
- Greater London Authority has commissioned 'Manufactured Housing Design Code' that will include spatial planning criteria such as storey heights and room dimensions and a freely available catalogue of standardized building components (structural and non-structural) (Cousins S., 2019)

Singapore:

- Government to target 70% adoption of DFMA in the built environment by 2025 (MND, 2021)
- Ministry of National Development (MND) has extended their flagship 'Construction Productivity and Capability Fund' until March 2022, with a total of over $1 bn sums allocated
- MND has also set aside $19m until January 2023 to support SMEs in adopting digital tools and accessing training
- Construction industry transformation map outlines the vision for DFMA, highly automated offsite production facilities, efficient and clean on-site installation processes, design for green buildings as well sustainable practices
- Integrated digital delivery (IDD) platforms along with DFMA are to work collaboratively with government and private sector construction projects
- Attract more talent, build engineering skills, provide pre-employment training and continuing education training

Identification of the technologies and relevant regulations/standards that will need to be developed in construction

Standards/regulations:

- Structural capacity compliances
- Quality compliances
- NCC amendment to recognize prefab buildings/products
- State warranty/insurance schemes to acknowledge off-site manufactured products and buildings
- Green certifications for off-site buildings acknowledging their improved energy performance

Technologies:

- BIM data architecture and standard format to store digital twins
- Testlabs tailored for construction tech for SMEs to compare their hardware and software architecture with that of the industry 4.0 technologies
- Product platform repository for standard products in off-site construction
- Scalable robotics and automation facilities for various aspects of off-site manufacturing
- IoT sensors integration with enterprise resource management software/BIM
- AR/VR integration with BIM models
- Cloud data hosting and transferable BIM models to each stakeholder

Case studies of DFMA in the building industry, lesson learnt and key benefits

Research shows that prefabricated construction can further be improved by incorporating DFMA into the early design of prefabricated panels and modules. The efficient early design, cloud-based collaboration and optimization can enhance the productivity of prefabricated construction. Since, DFMA is based on the principles of minimizing materials, time and labour involved, it is an effective optimization process for prefabricated products. The integration of DFMA in the early design can enhance efficiencies, productivity and contribute to optimizing manufacturing processes (Wasim et al. 2020a). However, the adaptation of DFMA principles in the early design for prefabricated products (panels and modules) still needs to be established for the modular industries in Australia.

Although the DFMA concepts are old and well established in other industries, there are limited case studies in the literature on the adaption of DFMA for prefabricated construction. The recent collaboration of the local plumbing industry and the Melbourne School of Design has proven that the principles of DFMA can significantly improve the prefabrication process and the overall cost of the high rise building residential construction project.

Case 1: Swanston Central, Melbourne CBD

The high-rise building was a 72 storey in which the DFMA based flatpack wall was installed. In that industry and research-led project, DFMA based manufacturing of flat pack wet walls was found to improve the efficiencies of design and the overall cost of the project (Vaz-Serra et al. 2021). There were several reasons for the better efficiencies obtained and cost optimization achieved through this project.

Key learnings:

- The unnecessary parts in the form of noggins were eliminated.
- Secondly, the workers in the factory who assembled the wet wall had lower hourly rates as compared to the workers on-site.
- It was found that an hourly rate of a licensed plumber could be 65-70% higher than the factory labour assembling the same plumbing parts.
- DFMA based manufacturing processes did not have the sequential delays or idle times which do exist in the conventional construction project (Consider Table 1).
- Thus, the cost and benefit analysis of this study reveals that a prefabricated wall panel can be 81% of the in-situ wall.
- This was the savings achieved for a bathroom of one apartment. Considering the magnanimity of the studied project being 72 stories with 27 bathrooms on each floor, the amount of savings that could be achieved if the whole building's wet walls were flat packed can easily be imagined.
- The savings in times (which has hidden cost) achieved in the assembly and installation of flat pack wall as compared to the conventional, prefab and DFMA based prefab is illustrated in Fig. 1.

Table 1 DFMA and conventional sequencing of flatpack wall (Vaz-Serra et al. 2019)

Step	Traditional Assembly Sequence	DfMA Sequence
1	Drywall marking and installation of metal tracks (top, bottom and vertical)	Drywall marking and installation of metal tracks (top, bottom and vertical)
2	Inform the supervisor	Inform the supervisor
3	Plumbing trade to arrive on-site and mark noggins	Plumbing trade installs the flat wall
4	Inform the supervisor	Inform the supervisor
5	Drywall trade to install noggins	Drywall trade to finish the wall installation with plasterboard, tiling and painting
6	Inform the supervisor	Plumbing trade to install final fittings on the wall
7	Plumbing trade to install pipes and support for fittings	
8	Inform the supervisor	
9	Drywall trade to finish the wall with plasterboard, tiling and painting	
10	Inform the supervisor	
11	Plumbing trade to install final fittings on the wall	

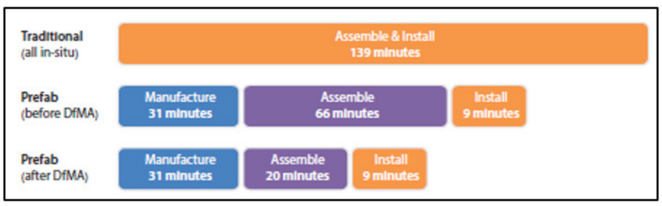

Figure 1 Benefits of DFMA based prefabrication of flatpack wet wall (Vaz-Serra et al. 2019).

Case 2: Conventional prefab vs DFMA enabled prefab

Similarly, another recent research conducted at the University of Melbourne on the DFMA based manufacturing of service components and non-structural timber wall for residential construction, demonstrates the savings obtained and benefits achieved (Wasim et al. 2020b). The comparison of in situ, conventional prefab at the factory and the DFMA based prefab was undertaken in that project. The observations of assembly times of timber wall and plumbing components at the actual construction project and at the prefab industry were carried out. Based on the prices of materials and the labour's hourly rates at the industry and the construction project, multiplied by the time spent on assembling, the respective costs for three different methods of prefabrication were computed and analysed. The results of this study demonstrated the benefits of DFMA based prefabrication over the conventional prefab for the overall cost of the project.

Key learnings:

- The savings of prefab coupled with DFMA could be 6% over non-DfMA prefab.
- The application of DFMA to the early design of the prefabricated products will be able to cover to some extent the additional cost that occurs due to the transportation, crane time and factory overheads.
- Furthermore, the framework for the adoption of DFMA based prefabrication was also proposed in that study.

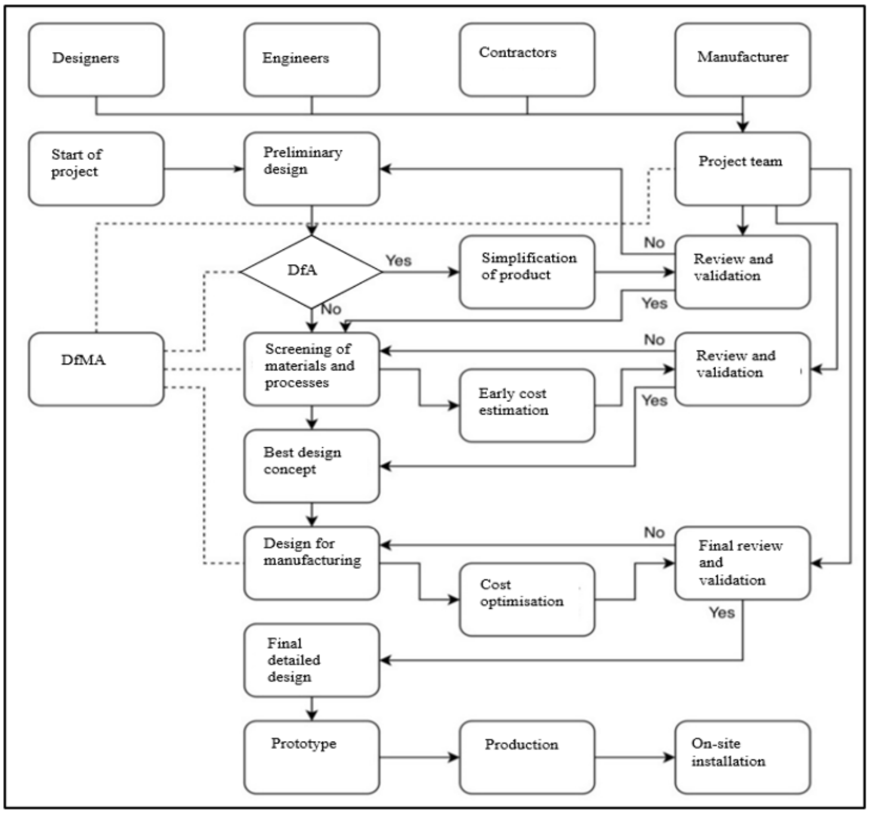

Figure 2 Collaboration of various stakeholders for DfMA-based prefabrication (Wasim et al. 2020).

Recently, Alfieri et al. (2020) proposed a BIM-based DFMA approach for construction and applied it to a case study of bathroom pod manufacturing in Italy. A workflow sequence for the Architecture Engineering Construction (AEC) sector in Italy was proposed. A framework for the adoption of the DFMA at various stages of construction from early design to post completions specific to the Italian industry was proposed with limitations. Similarly in another recent study, a framework for the integration of BIM and DFMA was proposed (Abrishami and Martín-Duran). Some of the benefits of prefabrication achieved by Mirvac in their projects were also mentioned in the report.

Case 3: Multiple examples by Mirvac Group

Tullamore Housing project

The Tullamore housing project delivered by Mirvac had four prefab houses and four conventional houses. The percentage savings obtained by prefab over non-prefab housings in duration, floor, labour, scaffoldings (high-risk works), wastages in mass and volume, noise, dust and traffic pollution and congestion are illustrated in Fig. 3.

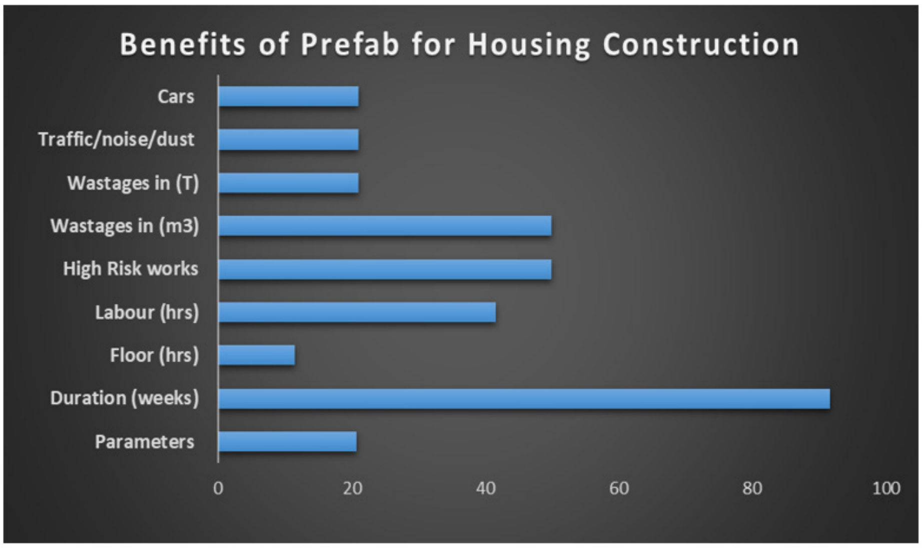

Figure 3 Percentage reductions for the housing construction project of Mirvac

Lea Victoria Housing Construction

By the adoption of a prefabricated bathroom pod, the labours savings of 96%, workhour savings of 88% and a total reduction of 94% in the number of days were obtained. Furthermore, the considerable savings in time-related to scheduling, communications (calls, meetings and emails), and inspections were quantified as shown in Figure 4. However, in the light of the aforementioned research case studies, the adoption of DFMA being an optimization process to these projects could have resulted in more savings of labour, man hours, materials, wastages and safety.

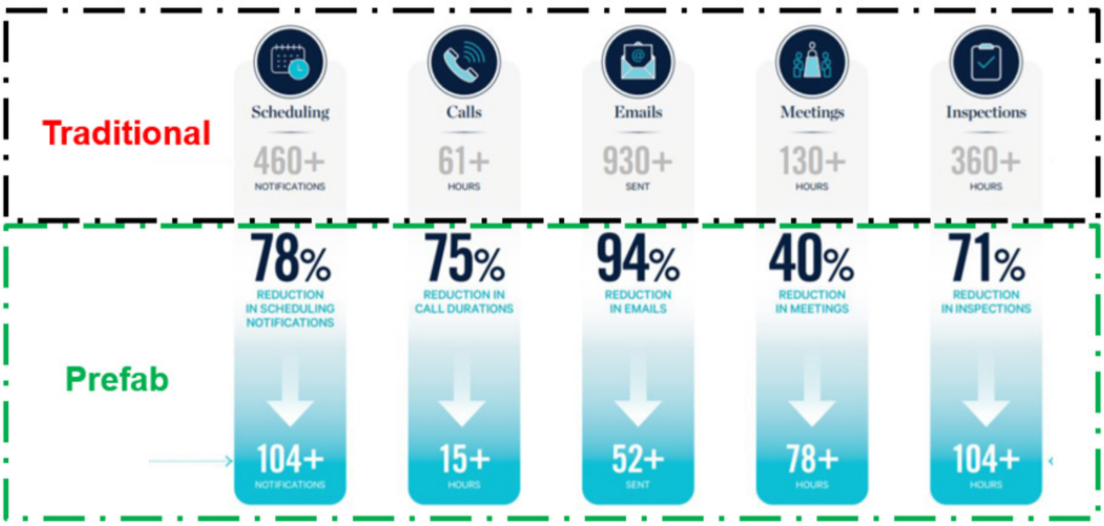

Figure 4 Non-construction but business-related benefits of prefab.

Finally, to conclude, it can be said that prefabrication or industrialized construction can be heavily benefited if the concepts of DFMA are applied at the early design which seems to be missing currently in the industry practices. Integration of DFMA tools to the cloud-based collaborative platforms such as Autodesk forge can further improve efficiencies, sustainability, productization, optimisation, circularity, and cost-effectiveness.

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