Paper submitted to the Hong Kong Joint Symposium 2022: City of the Future – Journey to Carbon Neutral Building, 23 Nov 2022 (Wed), Kowloon Shangri-la, Hong Kong

Apply design for manufacture and assembly (DfMA) thinking and offsite techniques to building services systems to enable future lean construction

Ir Dr. Sam C. M. Hui*

Department of Mechanical Engineering, The University of Hong Kong
Pokfulam Road, Hong Kong
* E-mail: cmhui@hku.hk (Adjunct Assistant Professor)

ABSTRACT

Design for manufacture and assembly (DfMA) refers to a set of principles for enabling a design process that facilitates the optimisation of all manufacture and assembly functions and contributes to the minimisation of cost and delivery time and the maximisation of quality and customer satisfaction. Originating from production industries, DfMA is considered an effective strategy for the construction industry to enhance productivity, quality, safety and sustainability. When DfMA is integrated with offsite techniques and applied to building services systems, it can support rapid-speed and efficient construction of building elements and components.

Applying DfMA enables the identification, quantification and elimination of waste or inefficiency in the manufacture and assembly of building components or systems. It can also be used as a benchmarking tool to study and select the most cost-effective materials, products or processes. DfMA can facilitate effective application of offsite prefabrication and modular construction technologies to provide optimisation of value and enhancement of productivity to the client and project team. Moreover, this approach can offer new opportunities to develop innovative building services engineering and construction processes, which will enable future lean construction.

Review of the global trends indicated that DfMA philosophy is an important basis for supporting industralised construction. To realise full potential of DfMA and offsite techniques, it is important to promote digital transformation and lean thinking across the whole construction industry. For building services systems, DfMA thinking can be applied to evaluate prefabricated components, sub-assemblies and integrated assemblies which are common techniques for offsite construction and fabrication.

(249 words)

Keywords: Design for manufacture and assembly (DfMA), offsite construction, building services systems, industrialised construction, lean construction.

1. INTRODUCTION

Design for manufacture and assembly (DfMA) refers to a set of principles for enabling a design process that facilitates the optimisation of all manufacture and assembly functions and contributes to the minimisation of cost and delivery time and the maximisation of quality and customer satisfaction (Chen & Lu, 2018). Originating from production industries, DfMA is considered an effective strategy for the construction industry to enhance productivity, quality, safety and sustainability (Laing O'Rourke, 2013). DfMA can be applied to various building works, civil and infrastructure works, as well as process plants. The scope for DfMA may cover structural, architectural, interior, as well as mechanical, electrical and plumbing (MEP) elements (Gibb, 1999). When DfMA is integrated with offsite techniques and applied to building services systems, it can support rapid-speed and efficient construction of building elements and components (Boon & Doig, 2019; CIC, 2022).

This research paper will explain the key concepts and principles of DfMA, assess its applications to building services systems, discuss the global trends and the situation in Hong Kong, and recommend practical strategies to enhance the adoption and effective use of the DfMA approach to enable future lean construction (LC). DfMA is one of the key enablers for industrialised construction (IC), offsite and modular techniques (Balfour Beatty, 2018). The use of building information modelling (BIM) as an integrated common data environment (CDE) can drive the overall digital construction and streamline the DfMA work processes towards a more collaborative and integrated solution (BCA, 2016).

2. DFMA AND OFFSITE TECHNIQUES

Offsite techniques such as prefabrication and modular construction are experiencing a significant expansion of interest and use as the construction industry seeks to improve productivity, quality, safety and sustainability performance while continuing to face workforce shortages, cost uncertainties and other challenges (BESA, 2015; Liu, Nzige & Li, 2019; Sands, 2019). It is believed that the DfMA approach can help enable offsite methods and related design solutions to be implemented more effectively.

2.1 History and Basic Principles of DfMA

DfMA is a family of methods belonging to the design for X (DfX) category which goal is to optimise the manufacturing and assembly phase of a product (Bralla, 1996; Formentini, Rodríguez & Favi, 2022; Huang, 1996). It is a proactive design approach that facilitates the optimisation of all manufacture and assembly functions for better project time, cost and quality delivery (Chen & Lu, 2018). DfMA originated during World War II when Ford and Chrysler applied it as a principle in their weapon production processes (Bogue, 2012; Lu *et al.*, 2021). Formal approaches to pioneer the philosophy of DfMA methodology emerged in the late 1960s and early 1970s. In the 1980s, DfMA software and tools were developed by Boothroyd and Dewhurst (Boothroyd *et al.*, 2011) and have been applied in various manufacturing companies and sectors, such as automobile and aerospace industries (Barbosa & Carvalho, 2013; Constance, 1992; Meeker, 2018). At first, it was used in manufacturing industries in the USA, Europe and Japan as analysis techniques to guide designers towards products which are easy to manufacture and assemble (Boothroyd, 1994). Nowadays, it has evolved into a mature design system and thinking philosophy which can be applied to other sectors and applications to reduce costs and increase profits (BDI, 2018).

DfMA focuses on ease of manufacture and efficiency of assembly bringing significant improvements in productivity, safety, quality and sustainability. Applying two design methodologies (Molloy, 1998): Design for Assembly (DFA) and Design for Manufacture (DFM), DfMA enables identification, quantification and elimination of waste or inefficiency in product manufacture and assembly as shown in Figure 1. The key principles of DfMA are minimisation, standardisation, and modularisation to guide design decisions (Gao, Jin & Lu, 2020) with the aim of using fewer design parts and assembling common "building blocks" modules into new products (BDI, 2018; Dewhurst, 2019; Meeker & Rousmaniere, 1996).

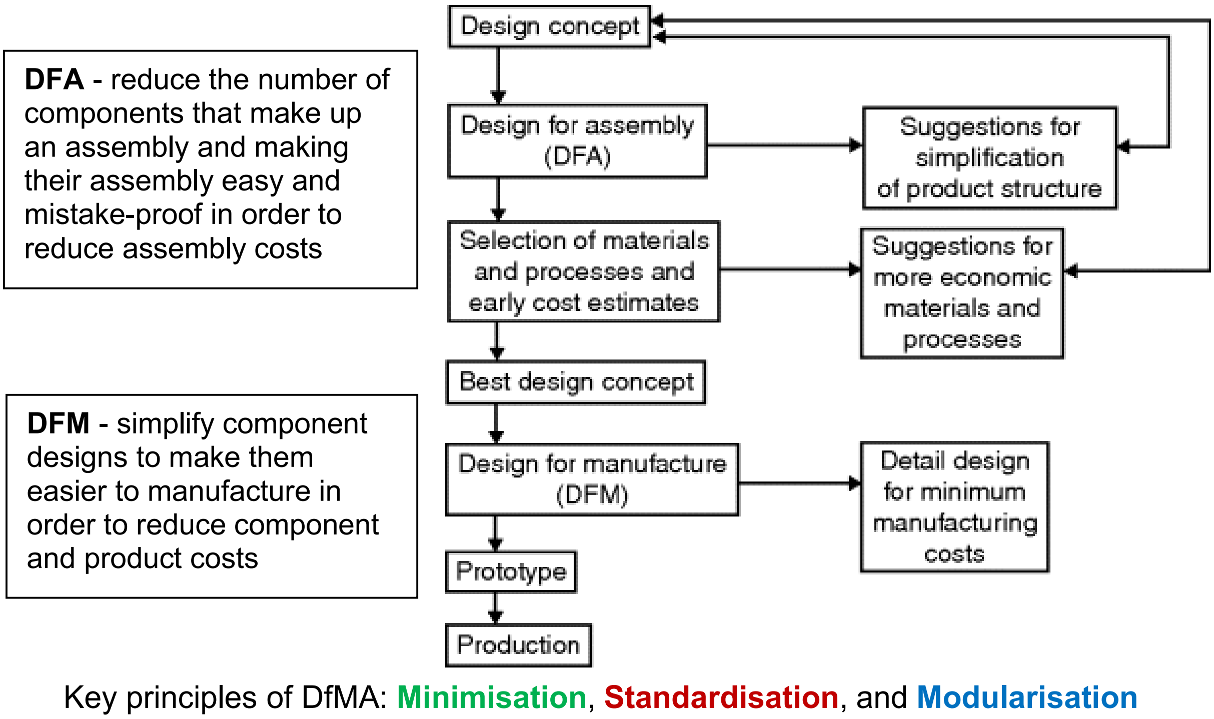

Figure 1. Basic concepts and procedures of DfMA (Boothroyd *et al.*, 2011; BESA, 2015)

2.2 DfMA in Construction

In construction, DfMA enables offsite manufacture of high-quality construction components and efficient assembly of the components onsite in a cost-effective manner (Lu *et al.*, 2021). The DFA concept is to design for minimising work onsite; whereas DFM enables manufacturing significant construction elements in a factory environment (RIBA, 2021; Tan *et al.*, 2020). In essence, DfMA in construction can be interpreted from three perspectives (Gao, Jin & Lu, 2020):

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

In practice, DfMA encompasses a wide spectrum of tools and technologies (both processes and products) that help design for ease of manufacturing and assembling of building spaces and components. The main goal of the DfMA approach is to work on the relationship between time, cost and quality in the construction industry by eliminating waste or any activity that does not add value to the client, designer or supply chain. The primary objective of such manufacturing-related approaches is to incorporate the knowledge of constructability in the design phase, generating potential savings in lead time. Lu *et al.* (2021) has pointed out that DfMA is a new and mixed 'cocktail' of opportunities and challenges to improve construction productivity with the advancement of construction materials, production and assembly technologies, and ever-strengthened logistics and supply chain management.

The DfMA approach offers a variety of solutions in response to project-specific drivers including sector, supply chain capability, degree of repeatability, logistics constraints, etc.

The higher the level of DfMA adoption, the greater the standardisation efficiencies that are possible. Prefabrication is regarded as the beginning level of industrialisation, which is followed by mechanisation, automation, robotics and reproduction (Bridgewater, 1993).

DfMA has a wide range of applications, from one-off small-scale to large-scale construction projects, and can benefit both cast insitu and prefabricated construction methods (Wilson, Smith & Deal, 1999a & b). Table 1 shows different categories of offsite construction (OSC) to be considered when adopting DfMA. The adoption of DfMA approach and offsite techniques is not a binary choice but a spectrum with different possible combinations. Smooth deployment of DfMA principles in construction can be achieved with the support of new project management/delivery methods and VDC technologies (Banks *et al.*, 2018; Gbadamosi *et al.*, 2019).

Table 1 Categories of offsite construction (Arif *et al.*, 2012; Gibb, 1999)

Category		**Definition**
1	Component manufacture & subassembly	Prefabricated units made in a factory and not considered for onsite production
2	Non-volumetric preassembly	Pre-assembled units which do not enclose usable space (e.g. timber roof trusses, flat panel units and panelised systems)
3	Volumetric preassembly	Pre-assembled units which enclose usable space and are typically fully factory finished internally, but do not form the building structure (e.g. toilet and bathroom pods)
4	Modular systems or buildings	Pre-assembled volumetric units which also form the actual structure and fabric of the building (e.g. prison cell units and hotel rooms)

2.3 Offsite Construction Techniques

To enhance productivity, offsite practice is receiving increasing attention as a process innovation along with DfMA (Bao *et al.*, 2022; Hyun H., Kim & Kim, 2022). In recent years, DfMA-oriented design has received increasing attention in studies on modular and prefabricated construction projects, in which considerable building components are manufactured offsite and then delivered to construction sites for assembly (Chen & Lu, 2018; Tan *et al.*, 2020; Yuan, Sun & Wang, 2018). Although DfMA and offsite methods have been used for many years in other industries including energy, automotive, aircraft and shipbuilding, their modern application methods in the construction industry are relatively new and still evolving (Taylor, 2009). The major constraints to OSC are value, processes, supply chain and knowledge (Blismas *et al.*, 2005). The main drivers to its adoption include cost, time, quality, health and safety, and sustainability.

OSC, offsite manufacturing (OSM) and offsite production (OSP) are largely interchangeable terms referring to the part of the construction process that is carried out away from the building site (BESA, 2015). This can be in a factory or sometimes in specially created temporary production facilities close to the construction site (or field/flying factories), as compared to traditional cast insitu construction. The term “offsite fabrication” was also used to refer to an industrial process and strategy which incorporates prefabrication, preassembly, standardisation and modularisation, with the aim to change the orientation of the project process from construction to manufacture and installation (Gibb, 1999).

2.4 Global trends

The construction industry is currently being transformed into a more integrated production to develop standardisation of products in line with the global market trends (Rastogi, 2017). The so called "Construction 4.0" vision (see Figure 2) is established based on three transformative processes: (a) product transformation, (b) digital transformation, and (c) transformation in project delivery processes and related business processes. Within the product transformation, the DfMA philosophy is an important basis for supporting IC, OSC, modular construction and prefabrication (Alfieri *et al.*, 2020; Gao, Jin & Lu, 2020; Laing O'Rourke, 2013; Lu *et al.*, 2021).

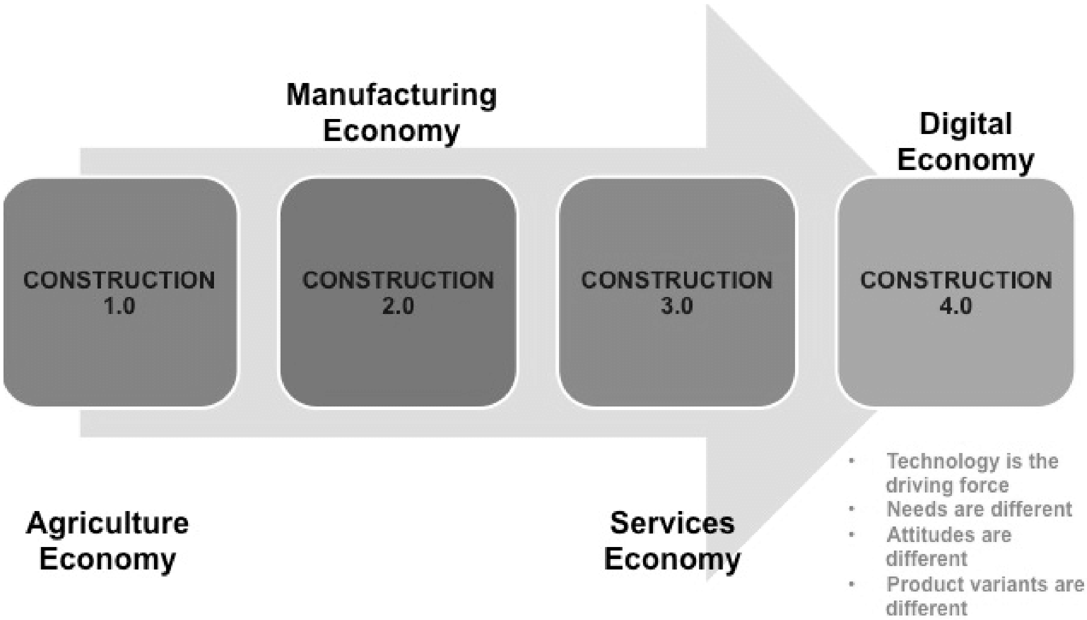

Figure 2. Evolution of Construction 4.0 (Sawhney, Riley & Irisarry, 2020)

In recent years, with wider acceptance and implementation of BIM in construction and infrastructure projects around the world, it does not only streamline the DfMA processes and operations for model-driven prefabrication, but also acts as a catalyst for a lean construction to improve business performance (Machado, Underwood & Fleming, 2016). It is believed that the synergies of BIM, DfMA and lean thinking will continue to grow in the coming future and will bring up new changes in technology, processes and people for design and construction. In fact, DfMA and lean thinking are more than simply a set of tools; they are a philosophy and design concepts that are shared throughout a value stream for organisational transformation and collaborative strategy.

The latest research findings show that OSC or prefabrication will motivate specialty contractors and suppliers to operate multiple fabrication shops close to market regions, where a shop can produce and deliver prefabricated components in a timely fashion and at a minimal cost (Ho, Kim & Zabinsky, 2022). The production planning in prefabrication supply chains and optimisation for job allocation are essential to the actual productivity improvements and cost minimisation.

OSC has the potential to improve construction efficiency by adopting additive manufacturing (AM) which can provide the benefits of fast prototyping and waste minimisation by using 3D printing techniques (Pasco, Lei & Aranas, 2022). With the support of DfMA thinking, the strategies to assess cost and material considerations such as production line breakdown structure (PBS) and value stream mapping (VSM) can be applied to the AM technologies to advance the OSC and material fabrication processes. This will benefit all construction disciplines including design of architectural, MEP and structural components. In addition, a modular approach (including product modularity and process modularity) can enhance the capability of DfMA, transform traditional design processes, enable efficient digital fabrication of OSC, and facilitate the product and process integration for taking advantage of modern automation and robotic technologies for construction production (Tan *et al.*, 2022).

2.5 Situation in Hong Kong

In Hong Kong, in recent years, the government has been promoting the adoption of Modular integrated Construction (MiC) in the construction industry (DevB, 2020) and some pilot MiC projects have been completed in Hong Kong (Pan & Hon, 2020), which is consistent with the global MiC development trends (Abdelmageed & Zayed, 2020). It is believed that MiC (an innovative construction method for achieving a building product delivery) and DfMA (a design approach for design and construction process management) can work together successfully to enhance productivity, quality and safety.

An emerging construction method for MEP works under the DfMA continuum known as Multitrade integrated Mechanical, Electrical and Plumbing (MiMEP) has recently been promulgated in Hong Kong. Different from the MiC for which free-standing modules (completed with finishes, fixtures and fittings) are manufactured in a factory then transported to site for installation (DevB, 2020; Pan & Hon, 2020), MiMEP focuses on MEP components/ equipment integrated into modules then delivered to and installed onsite. To apply MiMEP effectively, it is critical to design the MEP systems so that they can be fitted in each module with minimal external connections. Using the BIM technology, the works in the factory and offsite prefabrication of MEP systems can be well coordinated to enable seamless assembly or installation of different modules at the construction site (Dwyer, 2019). Also, completed modules are inspected for quality and statutory compliance before transporting to the site for assembly and installation. Three core design principles of MiMEP are:

- Offsite prefabrication and inspection
- Multi-trade integration and module maximisation (i.e. volumetric assembly with multi-trades integration)
- Plug and play (maximising efficiency of onsite installation works)

Evaluation of the barriers to wider DfMA adoption in Hong Kong has identified the following key concerns among the stakeholders (AECOM Asia Company Limited, 2021):

- Lack of demand
- Lack of expertise and training
- Upfront cost of adoption
- Unseen benefits/risks
- Fragmentation of the industry
- Lack of cross supply chain collaboration
- Industry inertia/culture against change
- No suitable procurement model
- Lack of standardisation
- Regulatory hurdles

It is found that the key enablers for DfMA/prefabrication application include knowledge, supporting organisation, government support, stakeholders, technologies and project-specific factors (Razak *et al.*, 2022). To promote the adoption and uptake of DfMA in Hong Kong, it is important to overcome the hindrance factors and provide a better understanding of the benefits of DfMA and its true potential.

3. APPLICATION TO BUILDING SERVICES SYSTEMS

Prefabricated MEP adopts the DfMA concept where components in MEP services and equipment are integrated into a sub-assembly offsite, for easy installation onsite (BCA & STAS, 2022). While OSC is commonly used in the MEP sector nowadays, such as preassembled and pre-wired pump sets, preassembled fan coil cooling units, and complete boiler rooms (BESA, 2015), little attention has been paid to the adoption of DfMA for MEP systems, particularly the integration with the structural design aspects.

In practice, the DfMA and prefabrication options for MEP components and systems will vary (Drigo & Deadman, 2019; Sands, 2019). Table 2 indicates major building services elements suitable for prefabrication. To apply the DfMA approach effectively, it is important to identify suitable areas for DfMA or prefabrication within the project (ACRA, 2020).

Table 2 Major building services elements suitable for prefabrication (Hui & Or, 2005)

Building services systems	Major elements
Mechanical ventilation and air conditioning	- Air duct system - Water pipework and fitting - Refrigerant pipework and fitting - Air conditioning equipment (e.g. air handling unit)
Fire services	- Water pipework and fitting - Pump sets and fittings - Smoke extraction system - Automatic fire detection & fire alarm systems
Plumbing and drainage	- Water supply pipework and fitting - Drainage pipework and fitting - Pump sets and fittings - Bathroom and toilet sanitary fittings
Electrical services	- Cable and busbar trunkings - Conduits and wiring - Power outlets and telecommunication - Electrical switchgear - Emergency generators

3.1 Potential Benefits

Assessment of the potential benefits of adopting the DfMA approach to building services systems indicates that it will contribute to the following positive aspects, which will result in overall reduction in costs and enhancement of productivity (AECOM Asia Company Limited, 2021):

- Shorter construction time
- Improved workmanship and quality control
- Economy of scale for mass production or mass customisation

- Simplified manufacturing and assembly processes
- Increased reliability, efficiency and productivity
- Reduced onsite works and impacts to the environment
- Reduce waste and environment impact
- Positive impact on workplace health and safety

In principle, DfMA provides a systematic procedure for analysing a proposed design from the point of view of assembly and manufacture. This procedure results in simpler and more reliable products, which are less expensive to assemble and manufacture. In addition, DfMA encourages dialogue between designers and the manufacturing engineers and any other individuals who play a part in determining final product costs during the early stages of design. This means that teamwork is encouraged and the benefits of simultaneous or concurrent engineering can be achieved for integrated product development. It is believed that the application of DfMA could improve the performance of the construction industry and provide a better industrialised building system (Razak *et al.*, 2022).

Under the DfMA continuum, prefabricated MEP systems is one of the game-changing technologies that can significantly improve productivity (BCA & STAS, 2022). It adopts the DfMA concept where components in MEP services and equipment are integrated into a subassembly off-site, for easy installation on site. Recent research indicates that the benefit of prefabrication is directly proportional to the level of modularity adopted (Chauhan *et al.*, 2022). A higher proportion of modules in a project product contributes to higher cost-benefits. On the other hand, prefabricated products with highly detailed module descriptions seem to lead to higher non-monetary benefits, such as better ergonomics and work satisfaction.

3.2 Major Considerations

The design and construction of prefab building systems demands a thorough understanding of their unique characteristics (Gunawardena & Mendis, 2022). It is found that MEP works is a less-explored area in prefab construction. There is a critical need to modularise MEP systems in prefab buildings, since the installation of building services currently takes up a considerable amount of time and remains a bottleneck in most prefab design and construction schedules. A combination of DfMA and OSC technologies will realise projects even faster and generate better profit margins for investors. In addition, OSC will also create a more quality-oriented practice and a safer working environment for upskilled building technicians.

When applied to building services systems, the DfMA approach requires a change in the relationship between design and construction/installation. The design should focus on the methods by which the project is to be delivered, using offsite manufactured components where possible and planning for efficient logistics and assembly of these components onsite. The core characteristic of DfMA is its component-driven, modularisation and standardisation approach. In addition, DfMA also requires planning, adapting and optimising the design to leverage offsite fabrication of components and onsite assembly (BCA, 2016).

When applying DfMA to building design and production, it is important to manage the project information process (Blake & Sands, 2021) and evaluate design management/freeze, logistics and tracking, vertical transport/hoisting, and quality management (end-to-end and factory) (BCA, 2017; Kuzmanovska & Aitchison, 2019). The process requires close collaboration among members of the design team, contractors/subcontractors, suppliers/manufacturers, and assemblers.

4. DISCUSSIONS

The DfMA philosophy is not entirely new in construction and there are overlaps between DfMA and other related concepts such as buildability, value management (VM), lean construction, and prefabrication (Lu *et al.*, 2021). The global market research reports on prefabrication and modular construction indicated the future is bright (Bertram *et al.*, 2019; DDA, 2020). The trends of DfMA and offsite adoption in construction around the world showed that the shift from onsite to offsite construction requires significant investment in manufacturing facilities (Bertram *et al.*, 2019). Other factors that determine the attractiveness of modular construction and offsite methods include supply chain and logistics, local site constraints, access to materials, quality perception and regulations.

4.1 From Manufacturing to Construction Process

If construction can be viewed as a manufacturing process, then a business process re-engineering can be applied to integrate the internal processes, enable concurrent engineering and remove historic divides (Crowley, 1998). The key success factor is to identify and implement appropriate models of manufacturing into the construction process (Winch, 2003). It should be noted that construction as an industry is defined very differently from other manufacturing industries. In general, manufacturing is usually product-based while construction is often project-based. Unlike manufactured products which are designed in-house, mass-produced, and sold to end users, construction products (e.g., housing, buildings, and infrastructure) are custom-made. Every construction product is contextualised within the geotechnical conditions of the site and its surroundings, the planned socio-economic function, and many other factors (Fox, Laurence & Cockerham, 2001).

To effectively implement DfMA and other manufacturing techniques, it is necessary to break down construction into sub-sectors with distinctive missions just as we have broken down manufacturing. As manufacturing and construction converge, it is possible to utilise manufacturing's expertise in mass production and construction's ability to design and build a highly customised complex product, such as in industrialised housing (Gann, 1996).

Moreover, by combining the BIM capabilities in the DfMA method with mass customisation into a framework, it can enable customers to participate in the OSC configuration process (Bakhshi *et al.*, 2022). A BIM-based approach for DfMA can extend the technological potential of BIM for offsite manufacturing (Abanda, Tah & Cheung, 2017; Alfieri *et al.*, 2020) and optimise the design and assembly of OSC (Arashpour *et al.*, 2015; Gbadamosi *et al.*, 2019). The digitally enabled DfMA and adoption of integrated project delivery (IPD) principles have the potential to optimise product development in modern construction (Arashpour *et al.*, 2018). Furthermore, DfMA encourages multidisciplinary collaborations in product development where manufacturing and resourcing constraints are considered in designing parts and assemblies.

4.2 Lean Construction

The development of lean construction is fundamental for improving construction productivity, quality and delivery of value to clients and users (Autodesk, 2020; Do, 2022; Tzortzopoulos, Kagioglou & Koskela, 2020). LC is a new way to manage construction projects with the aims to minimise the waste of materials and time and to generate the maximum value (Li *et al.*, 2019). LC methods promote a collaborative and efficient project delivery to identify value for a client, establish demand-based flows of information and products, eliminate waste (nonvalue added). The integration of BIM, DfMA, LC and sustainability are important in technological applications for OSC (Jin *et al.*, 2018).

Applying DfMA enables the identification, quantification and elimination of waste or inefficiency in the manufacture and assembly of building components or systems. It can also be used as a benchmarking tool to study and select the most cost-effective materials, products or processes. Taking advantage of an integrated planning and supply chain optimisation strategy, it can facilitate effective application of offsite prefabrication and modular construction technologies to provide optimisation of value and enhancement of productivity to the client and project team. Moreover, this approach can offer new opportunities to develop innovative building services engineering and construction processes, which will enable future LC.

4.3 Recommended Strategies

In order to drive DfMA adoption to enhance productivity for MEP works in Hong Kong, four areas of practical strategies have been identified (AECOM Asia Company Limited, 2021).

- Raise awareness by education and promotion
- Engage stakeholders to create the demand
- Enhance supply chain collaboration/ecosystem
- Build up local capability and skills

At present, OSC is not a mainstream technique in the industry and the lack of expertise and knowledge of project stakeholders were identified as the major limitation (Hyun H., Kim & Kim, 2022). It is important to develop the DfMA ecosystem in the local construction industry (de Meyer & Mittal., 2019). To support the project stakeholders to adopt DfMA and OSC, practical guidelines to apply DfMA and critical information on the OSC design process can be developed (CIC, 2022). In particular, the DfMA considerations and strategies for MEP planning must be clarified and studied carefully.

In practice, there is a need for more efficient information management and nomenclature for OSC (Lou *et al.*, 2022). It is important to promote efficient collaboration among the stakeholders to balance different needs and arrive at common understandings. To address this issue, development and application of an integrated management system will help integrates the entire supply chain of the OSC project to achieve the improvements in work efficiency (Jang, Lee & Son, 2022).

From the perspective of the government and developers, the development strategy optimisation for OSC projects should simultaneously maximises both short-term economic and long-term social benefits (Dou *et al.*, 2022). Therefore, to drive OSC progress effectively, the planning of the related policies should evaluate the impact of different intervention methods, such as direct subsidies, indirect subsidies, and prefabrication ratio requirements. Very often, indirect subsidies and capacity building are more effective than market regulation.

5. CONCLUSIONS

DfMA philosophy is an important basis and enabler to industralised construction for enhancing project delivery and improving productivity through lean construction thinking and digital fabrication techniques. Many countries around the world are developing policies and resources to promote innovative DfMA applications. Building services systems is one of the less-explored areas which requires further research and development to upgrade the DfMA knowledge and proficiency. At present, the key factors affecting taking up of the DfMA approach in Hong Kong include awareness, market demand, supply chain maturity and local skill capability. To realise full potential of DfMA and offsite techniques, it is important to promote digital transformation, lean thinking and industrialised construction across the whole construction industry.

It is believed the application of DfMA to building services systems requires a paradigm shift not only in design methodology but also in professional practice process. DfMA thinking can be applied to evaluate prefabricated components, sub-assemblies and integrated assemblies which are common techniques for OSC and fabrication. It can also be used to enable efficient digital fabrication and modern automation and robotic technologies for construction production. In line with the transformative processes of Construction 4.0 vision, the DfMA philosophy will support further development of OSC, modular construction and prefabrication. It is very important for Hong Kong to catch up the global trends and explore the full potential of DfMA in enhancing the productivity and competitiveness.

ACKNOWLEDGMENTS

Sincere thanks are expressed to Mr. C. K. Wong of AECOM Asia Company Limited and the Construction Industry Council, Hong Kong for offering useful comments to this research and providing supports for the research analysis.

REFERENCES

Abanda F. H., Tah J. H. M. and Cheung F. K. T., 2017. BIM in off-site manufacturing for buildings, *Journal of Building Engineering*, 14: 89-102.

Abdelmageed S. & Zayed T., 2020. A study of literature in modular integrated construction - Critical review and future directions, *Journal of Cleaner Production*, 277: 124044.

ACRA, 2020. DfMA in Air Conditioning, *ACRA Newsletter*, Winter 2020, page 8-12, Hong Kong Air Conditioning and Refrigeration Association Ltd. (ACRA), Hong Kong. http://www.acra.org.hk/webPage/download/ACRA_WIN_20_Part1.pdf

AECOM Asia Company Limited, 2021. *Reference Materials - Adopting DfMA for MEP Works*, Construction Industry Council, Hong Kong. http://www.cic.hk/files/page/51/Reference%20Materials%20-%20Adopting%20DfMA%20for%20MEP%20Works_20210930.pdf

Alfieri E., Seghezzi E., Sauchelli M., Di Giuda G. M. & Masera G., 2020. A BIM-based approach for DfMA in building construction: framework and first results on an Italian case study, *Architectural Engineering and Design Management*, 16 (4) 247-269.

Arashpour M., Kamat V., Bai Y., Wakefield R. & Abbasi B., 2018. Optimization modeling of multi-skilled resources in prefabrication: Theorizing cost analysis of process integration in off-site construction, *Automation in Construction*, 95: 1-9.

Arashpour M., Wakefield R., Blismas N. & Minas J., 2015. Optimization of process integration and multi-skilled resource utilization in off-site construction, *Automation in Construction*, 50: 72-80.

Arif M., Bendi D., Sawhney A. & Iyer K. C., 2012. State of offsite construction in India-Drivers and barriers, *Journal of Physics: Conference Series*, 364: 12109.

Autodesk, 2020. *An Introduction to Lean Construction for Today's Construction Professionals*, Autodesk Construction Cloud. https://getconstructioncloud.autodesk.com/lean-construction-apac-ty/

Bakhshi S., Chenaghlou M. R., Rahimian F. P., Edwards D. J. & Dawood N., 2022. Integrated BIM and DfMA parametric and algorithmic design based collaboration for supporting client engagement within offsite construction, *Automation in Construction*, 133: 104015.

Balfour Beatty, 2018. *25% by 2025, Streamlined Construction: Seven steps to offsite and modular building*, Balfour Beatty, London. https://www.balfourbeatty.com/media/317714/streamlined-construction-seven-steps-to-offsite-and-modular-building.pdf

Banks C., Kotecha R., Curtis J., Dee C., Pitt N. & Papworth R., 2018. Enhancing high-rise residential construction through design for manufacture and assembly – a UK case study, *Proceedings of the Institution of Civil Engineers - Management, Procurement and Law*, 171 (4) 164-175.

Bao Z., Laovisutthichai V., Tan T., Wang Q. & Lu W., 2022. Design for manufacture and assembly (DfMA) enablers for offsite interior design and construction, *Building Research and Information*, 50 (3) 325-338.

Barbosa G. F. & Carvalho J., 2013. Design for Manufacturing and Assembly methodology applied to aircrafts design and manufacturing, *IFAC Proceedings Volumes*, 46 (7) 116-121.

BCA, 2016. *BIM for DfMA (Design for Manufacturing and Assembly) Essential Guide*, Building and Construction Authority (BCA), Singapore.

BCA, 2017. *Design for Manufacturing and Assembly (DfMA): Prefabricated Prefinished Volumetric Construction*, Building and Construction Authority (BCA), Singapore.

BCA & STAS, 2022. *Prefabricated Mechanical, Electrical and Plumbing (MEP) Systems: Design for Manufacturing and Assembly (DfMA) Guidebook*, Version 2, Building and Construction Authority (BCA) and Specialists Trade Alliance of Singapore (STAS), Singapore. https://stas.org.sg/prefab-mep-guidebook/

BDI, 2018. *DFMA Design for Manufacture & Assembly: Reduce Costs Increase Profits, a White Paper for Corporate Management*, Boothroyd Dewhurst, Inc., Wakefield, RI. https://www.dfma.com/resources/dfmawp.asp

Bertram N., Fuchs S., Mischke J., Palter R., Strube G. & Woetzel J., 2019. *Modular construction: From projects to products*, McKinsey & Company. https://www.mckinsey.com/industries/capital-projects-andinfrastructure/our-insights/modular-construction-from-projects-toproducts

BESA, 2015. *An Offsite Guide for the Building and Engineering Services Sector*, Building and Engineering Services Association (BESA), London.

Blake N. & Sands J., 2021. *Project Information Process*, BG 78/2021, Building Services Research and Information Association (BSRIA), Bracknell, Berkshire, UK.

Blismas N. G., Pendlebury M., Gibb A. & Pasquire C., 2005. Constraints to the use of off-site production on construction projects, *Architectural Engineering and Design Management*, 1 (3) 153-162.

Bogue R., 2012. Design for manufacture and assembly: background, capabilities and applications, *Assembly Automation*, 32 (2) 112-118.

Boon K. S. & Doig L., 2019. DFMA for Prefabricated Mechanical, Electrical and Plumbing (MEP) Systems, *Arcadis Insights*, Issue 2/2019 - March 2019.

Boothroyd G., 1994. Product design for manufacture and assembly, *Computer-Aided Design*, 26 (7) 505-520.

Boothroyd G., Dewhurst P., Knight W. A. & Anthony W., 2011. *Product Design for Manufacture and Assembly*, 3rd ed, CRC Press, Boca Raton, FL.

Bralla J. G., 1996. *Design for Excellence*, McGraw-Hill, New York.

Bridgewater, C., 1993. Principles of design for automation applied to construction tasks, *Automation in Construction*, 2 (1) 57-64.

Chauhan K., Peltokorpi A., Lavikka R. & Seppänen O., 2022. The monetary and non-monetary impacts of prefabrication on construction: the effects of product modularity, *Buildings*, 12: 459.

Chen K. & Lu W., 2018. Design for manufacture and assembly oriented design approach to a curtain wall system: a case study of a commercial building in Wuhan, China, *Sustainability*, 10 (7) 2211.

CIC, 2022. *Reference Materials on Adopting DfMA for MEP Works (A Concise Guide)*, Construction Industry Council, Hong Kong. https://www.cic.hk/files/page/51/Reference%20Material%20on%20Adopting%20DfMA%20for%20MEP%20Works%20(A%20Concise%20Guide).pdf

Constance J., 1992. DFMA: learning to design for manufacture and assembly, *Mechanical Engineering-CIME*, 114 (5) 70-74.

Crowley A., 1998. Construction as a manufacturing process: Lessons from the automotive industry, *Computers & Structures*, 67 (5) 389-400.

DDA, 2020. *Prefabrication and Modular Construction 2020*, SmartMarket Report, Dodge Data & Analytics (DDA), Bedford, MA. http://www.modular.org/documents/public/PrefabModularSmartMarketReport2020.pdf

de Meyer A. & Mittal S., 2019. *Developing the DfMA Ecosystem in Singapore's Construction Industry*, SMU-19-0036, Singapore Management University, Singapore.

DevB, 2020. Modular Integrated Construction (MiC), Development Bureau Technical Circular (Works) No. 2/2020, Development Bureau (DevB), Hong Kong.

Dewhurst N. P., 2019. Design for Manufacture and Assembly: History, an overview, and a design story, presentation at the *2019 International Forum on DFMA*, Boothroyd Dewhurst, Inc., Providence, RI. https://www.dfma.com/forum/2019pdf/dewhurstpres.pdf

Do D., 2022. The Art and Philosophy of Lean Construction. https://leanconstructionblog.com/art-and-philosophy-of-lean-construction-ebook.html

Drigo R. & Deadman J., 2019. DfMA Building Services: What have we done and where are we going?, *CIBSE ANZ Technical Seminar: Piecing It All Together – Prefabrication and Modular Construction*, Sydney, Australia.

Dwyer T., 2019. Module 154: Offsite prefabrication driven by DfMA, CIBSE Journal CPD Programme. https://www.cibsejournal.com/cpd/modules/2019-11-dma/

Formentini G., Rodríguez N. B. & Favi C., 2022. Design for manufacturing and assembly methods in the product development process of mechanical products: a systematic literature review, *The International Journal of Advanced Manufacturing Technology*, 120: 4307-4334.

Fox S., Laurence M. & Cockerham, G., 2001. Design for manufacture: A strategy for successful application to buildings, *Construction Management and Economics*, 19 (5) 493-502.

Gann D. M., 1996. Construction as a manufacturing process? Similarities and differences between industrialized housing and car production in Japan, *Construction Management and Economics*, 14 (5) 437-450.

Gao S., Jin R. & Lu W., 2020. Design for manufacture and assembly in construction: a review, *Building Research & Information*, 48 (5) 538-550.

Gbadamosi A.-Q., Mahamadu A.-M., Oyedele L. O., Akinade O. O., Manu P., Mahdjoubi L. & Aigbavboa C., 2019. Offsite construction: Developing a BIM-Based optimizer for assembly, *Journal of Cleaner Production*, 215: 1180-1190.

Gibb A. G. F., 1999. *Off-site Fabrication: Prefabrication, Pre-assembly and Modularisation*, Whittles Pub., Latheronwheel.

Gunawardena T. & Mendis P., 2022. Prefabricated building systems—design and construction, *Encyclopedia*, 2: 70-95.

Ho C., Kim Y.-W. & Zabinsky Z. B., 2022. Prefabrication supply chains with multiple shops: Optimization for job allocation, *Automation in Construction*, 136: 104155.

Huang G. Q. (ed.), 1996. *Design for X: Concurrent engineering imperatives*, Chapman & Hall, London.

Hui S. C. M. and Or G. K. C., 2005. Study of prefabricated building services components for residential buildings in Hong Kong, In *Proceedings of the Hubei-Hong Kong Joint Symposium 2005*, 1-2 July 2005, Wuhan, China, pp. 88-97. http://ibse.hk/cmhui/hubei2005.pdf

Hyun H., Kim H.-G. & Kim J.-S., 2022. Integrated off-site construction design process including DfMA considerations, *Sustainability*, 14 (7) 4084.

Jang Y., Lee J.-M., & Son J., 2022. Development and application of an integrated management system for off-site construction projects, *Buildings*, 12: 1063.

Jin R., Gao S., Cheshmehzangi A. & Aboagye-Nimo E., 2018. A holistic review of off-site construction literature published between 2008 and 2018, *Journal of Cleaner Production*, 202: 1202-1219.

Kuzmanovska I. & Aitchison M., 2019. DfMA in Building Design and Production: Uses and Abuses, paper & presentation at *the 2019 International Forum on DFMA*, Boothroyd Dewhurst, Inc., Providence, RI. https://www.dfma.com/forum/2019pdf/kuzmanovskapres.pdf

Laing O'Rourke, 2013. The future of DfMA is the future of construction, *Engineering Excellence Journal (EEJ)*, 2013 edition. http://www.laingorourke.com/~/media/lor/files/lor-engineering-excellence-journal-2013.pdf

Li L., Li Z., Li X. & Wu G., 2019. A review of global lean construction during the past two decades: analysis and visualization, *Engineering, Construction, and Architectural Management*, 26 (6) 1192-1216.

Liu G., Nzige J. H. & Li K., 2019. Trending topics and themes in offsite construction (OSC) research, *Construction Innovation*, 19 (3) 343-366.

Lou J., Lu W., Xu J., Li X. & Wang J., 2022. Nomenclature for offsite construction, *Building Research & Information*, DOI: 10.1080/09613218.2022.2039586.

Lu W., Tan T., Xu J., Wang J., Chen K., Gao S. & Xue F., 2021. Design for manufacture and assembly (DfMA) in construction: the old and the new, *Architectural Engineering and Design Management*, 17 (1-2) 77-91.

Machado M., Underwood J. & Fleming A. J., 2016. Implementing BIM to streamline a design, manufacture, and fitting workflow: a case study on a fit-out SME in the UK, *International Journal of 3-D Information Modeling*, 5 (3) 31-46.

Meeker D., 2018. DFMA Back To Its Roots: The Evolution and Application of DFMA, paper & presentation at the *2018 International Forum on DFMA*, Boothroyd Dewhurst, Inc., Providence, RI.

Meeker D. G. & Rousmaniere A., 1996. *DFMA and Its Role in the Integrated Product Development Process*, MIT, June.

Molloy O., 1998. *Design for Manufacturing and Assembly: Concepts, Architectures and Implementation*, Chapman & Hall, London & New York.

Pan W. & Hon C. K., 2020. Briefing: Modular integrated construction for high-rise buildings, *Proceedings of the Institution of Civil Engineers - Municipal Engineer*, 173 (2) 64-68.

Pasco J., Lei Z. & Aranas, C. Jr., 2022. Additive manufacturing in off-site construction: review and future directions, *Buildings*, 12: 53.

Rastogi S., 2017. Construction 4.0: the 4th generation revolution, In *Proceedings of the ILCC 2017 Indian Lean Construction Conference*, IIT Madras, Chennai , India, p. C288-C298.

https://www.researchgate.net/publication/331131645_CONSTRUCTION_40_THE_4_th_GENERATION_REVOLUTION
Razak M. I. A., Khoiry M. A., Badaruzzaman W. H. W. & Hussain A. H., 2022. DfMA for a better industrialised building system, *Buildings*, 12: 794.
RIBA, 2021. *DfMA Overlay to the RIBA Plan of Work: Mainstreaming Design for Manufacture and Assembly in Construction*, 2nd Edition, Royal Institute of British Architects (RIBA), London, UK. https://www.architecture.com/knowledge-and-resources/resources-landing-page/dfma-overlay-to-the-riba-plan-of-work
Sands J., 2019. *Offsite Construction for Building Services*, Topic Guide TG 17/2019, Building Services Research and Information Association (BSRIA), Bracknell, Berkshire, UK.
Sawhney B., Riley M. & Irizarry J., 2020. *Construction 4.0: An Innovation Platform for the Built Environment*, Routledge, London.
Tan T., Lu W. S., Tan G. Y., Xue F., Chen K., Xu J. Y., Wang J. & Gao S., 2020. Construction-oriented design for manufacture and assembly (DfMA) guidelines, *ASCE Journal of Construction Engineering and Management*, 148 (8) 04020085.
Tan T., Mills G., Papadonikolaki E., Li B. & Huang J., 2022. Digital-enabled Design for Manufacture and Assembly (DfMA) in offsite construction: A modularity perspective for the product and process integration, *Architectural Engineering and Design Management*, DOI: 10.1080/17452007.2022.2104208.
Taylor S., 2009. *Offsite Production in the UK Construction Industry – A Brief Overview*, prepared by HSE, Construction Industry Research and Information Association (CIRIA), London. http://ciria.org/buildoffsite/downloads/off-site_production_june09.pdf
Tzortzopoulos P., Kagioglou M. & Koskela L. (eds.), 2020. *Lean Construction: Core Concepts and New Frontiers*, Routledge, Oxon & New York.
Wilson D. G., Smith M. H. & Deal J., 1999. *Prefabrication and Preassembly: Applying the Techniques to Building Engineering Services*, Advanced Construction Techniques ACT 1/99, Building Services Research and Information Association (BSRIA), Bracknell, Berkshire, UK.
Wilson D. G., Smith M. H. & Deal J., 1999. *Prefabrication and Preassembly: Successful Application in Building Engineering Services*, Advanced Construction Techniques ACT 2/99, Building Services Research and Information Association (BSRIA), Bracknell, Berkshire, UK.
Winch G., 2003. Models of manufacturing and the construction process: the genesis of re-engineering construction, *Building Research & Information*, 31 (2) 107-118.
Yuan Z., Sun C. & Wang Y., 2018. Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings, *Automation in Construction*, 88 (2018) 13-22.