CONSTRUCTION INDUSTRY COUNCIL
建造業議會

REFERENCE MATERIAL on Adopting DfMA for MEP Works (A Concise Guide)

Design Principles of MiMEP

Offsite Prefabrication

MultiTrade Integration and Module Maximization

Plug and Play

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Contents

Foreword ... iii

Disclaimer ... iv

Acknowledgement ... v

List of Abbreviations ... vi

1. Fundamental Principles ... 1

1.1 What is DfMA? ... 2

1.2 DfMA in Construction ... 4

1.2.1 DfMA Applications and Industrialised Construction ... 4

1.2.2 Degree and Methods of DfMA Adoption ... 6

1.3 DfMA for MEP Works ... 7

1.3.1 MEP Prefabrication ... 7

1.3.2 MiMEP Concept ... 9

1.3.3 Important Tasks for MEP Works ... 11

2. Planning and Design Development ... 13

2.1 DfMA Strategies ... 15

2.1.1 Design Options ... 15

2.1.2 DfMA and Construction Strategy ... 16

2.1.3 BIM Tasks ... 16

2.2 Procurement Tasks ... 17

2.2.1 Early Contractor Involvement (ECI) ... 17

2.2.2 Collaborative Approach ... 19

2.2.3 Quality Standards and Statutory Requirements ... 20

2.3 Design Process ... 21

2.3.1 Project Team and Design Workflow ... 21

2.3.2 Design and Configuration of MEP Modules ... 22

2.3.3 Coordination of Design Elements ... 23

2.3.4 Design for Maintenance ... 24

Contents

3. Implementation 26

3.1 Project Administration and Management 27

3.1.1 Method Statements and Tolerances 27

3.1.2 Lean Construction and Management 28

3.1.3 Design for Assembly and Offsite Manufacturing 29

3.1.4 Progress, Scheduling and Quality Assurance 30

3.1.5 Inspection, Commissioning and Approval 31

3.1.6 Lead Coordinator and Work Sequence 31

3.1.7 Payment Model and Arrangement 32

3.2 Construction Process and Logistics 32

3.2.1 Logistics Considerations 33

3.2.2 Obligation of the Main Contractor 34

3.2.3 Delivery to Site 35

3.2.4 Just in Time (JIT) Concept 35

3.2.5 Lifting and Positioning 36

3.3 Handover and Operation 38

3.3.1 MEP Systems Operation and Maintenance 39

3.3.2 As-built Information and Feedbacks 39

References 40

Appendix 1 - Terminology 43

Foreword

Originating from production industries, Design for Manufacture and Assembly (DfMA) is considered as an enabler to industrialise construction for enhancing project delivery in the areas of productivity, safety, sustainability and quality. It is also one of the key enablers for industrialised construction. Recently, an emerging construction method for MEP works under the DfMA continuum known as Multitrade integrated Mechanical, Electrical and Plumbing (MiMEP), focuses on integrating MEP components/ equipment into modules for subsequent installation on site. MiMEP has been proven as an effective approach to achieve significant enhancement in productivity, work efficiency and quality.

This Reference Material (Concise version) provides key considerations and practical strategies from planning and design phase to implementation phase, encouraging practitioners to make use of offsite prefabrication solutions out of the DfMA spectrum and fully utilize the BIM tool together with lean manufacturing / construction principles to achieve value maximisation and waste minimisation.

While this concise version serves as a preliminary guide for practitioners to adopt DfMA approach / MiMEP in the upcoming construction projects, readers are suggested to refer to the full version of this Reference Material in the Construction Industry Council's website, which includes full explanations on DfMA / MiMEP, case studies and sample specifications for MiMEP, as well as to seek professional advice from the designers and specialist subcontractors.

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Hospital Authority, Hong Kong
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AECOM, UK
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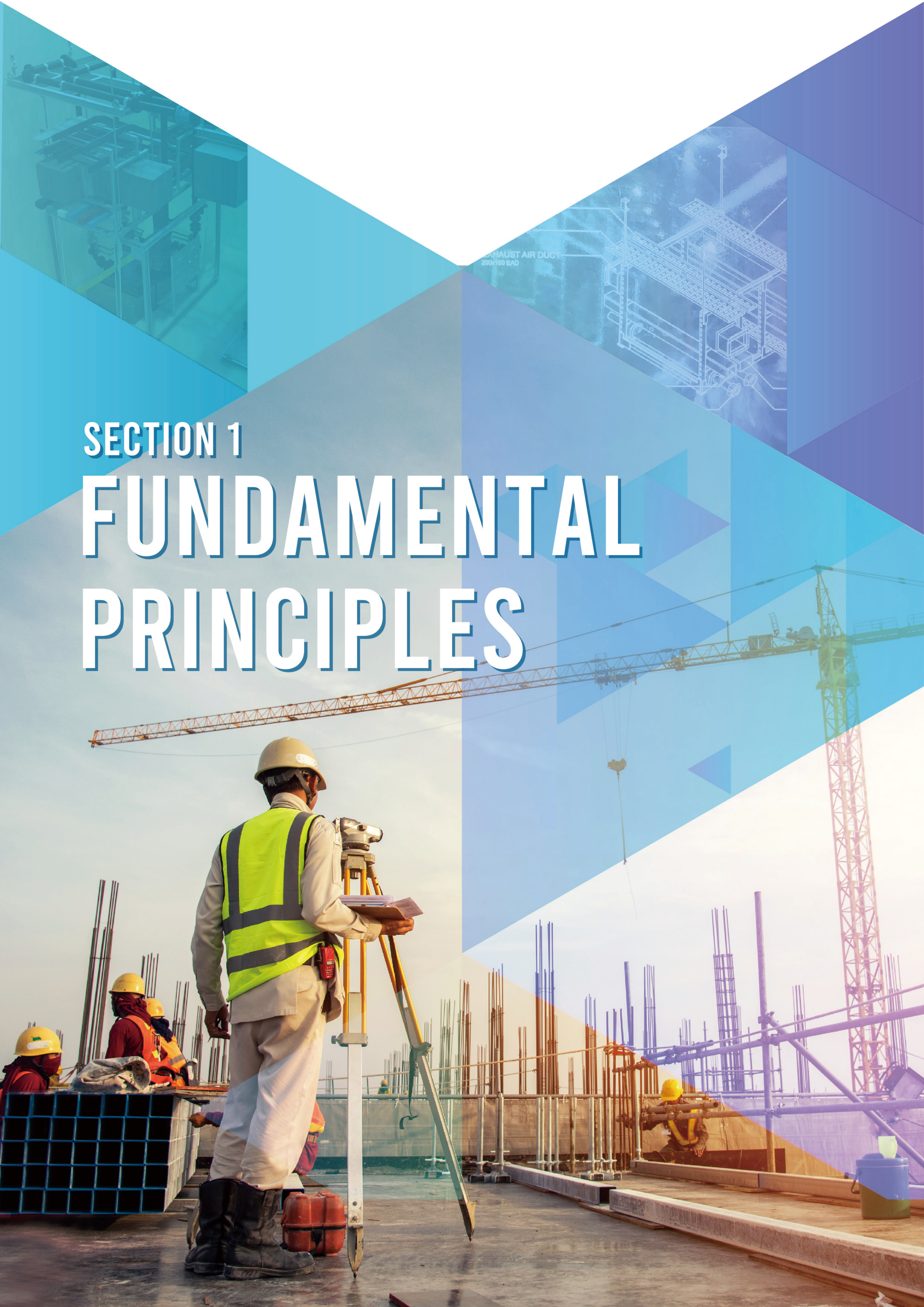
Bouygues Construction, Singapore
Bryden Wood, UK
Building and Construction Authority, Singapore
Crown House Engineering, UK
Dragages, Singapore
GRAHAM Group, UK
Hilti Group
Laing O'Rourke, UK
Gammon Construction Limited, Singapore
Prism Offsite Manufacturing, UK
SES Engineering Services Limited, UK
Specialists Trade Alliance of Singapore
The Garthfoot Consultancy, UK
Trans Equatorial Engineering, Singapore

List of Abbreviations

ACRA	Hong Kong Air Conditioning and Refrigeration Association Ltd.
AHU	Air handling unit
ATIF	Assembling, transporting and installation frame
BCA	Building and Construction Authority, Singapore
BDI	Boothroyd Dewhurst, Inc.
BESA	Building and Engineering Services Association, UK
BIM	Building information modelling
BSI	British Standards Institution
BSRIA	Building Services Research and Information Association, UK
CDE	Common data environment
CIBSE	Chartered Institution of Building Services Engineers, UK
CIC	Construction Industry Council, Hong Kong
CSD	Combined/coordinated services drawings
D&B	Design and Build
DEVB	Development Bureau, Hong Kong
DFA	Design for Assembly
DFM	Design for Manufacture
DfMA	Design for manufacture and assembly
ECI	Early Contractor Involvement
EOTA	European Organisation for Technical Assessment
EPC	Engineering, Procurement&Construction
FSD	Fire Services Department, Hong Kong
FSI	Fire service installation
GBP	General building plan
GIS	Geographic information system
GPS	Global positioning system
IC	Industrialised construction
JIT	Just-in-Time
LOR	Laing O'Rourke, UK
MEP	Mechanical, electrical and plumbing
MiC	Modular integrated Construction
MiMEP	Multitradeintegrated Mechanical, Electrical and Plumbing
O&M	Operation and maintenance
OSC	Offsite Construction
OSM	Offsite Manufacture
PCWAs	Public Cargo Working Areas
PMV	Pre-manufactured value
PNAP	Practice Notes for Authorised Persons
Prefab	Prefabrication
RIBA	Royal Institute ofBritish Architects
T&C	Testing & commissioning
UK	United Kingdom
VDC	Virtual design and construction
VR	Virtual Reality
VSM	Value stream mapping
WIP	Work-in-progress
WLP	Wide Load Permit

SECTION 1

FUNDAMENTAL PRINCIPLES



1 Fundamental Principles

Design for manufacture and assembly (DfMA) 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). Originating from production industries, DfMA is considered a potential approach with many benefits for the construction industry to enhance productivity and quality (Laing O'Rourke, 2013; McKinsey Global Institute, 2017).

1.1 What is DfMA?

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 1.1. A summary of the key terminology related to DfMA is given in Appendix 1.

DFA

reduce the number of components to making assembly easy and mistake-proof

DFM

simplify component designs for efficient manufacture and fabrication

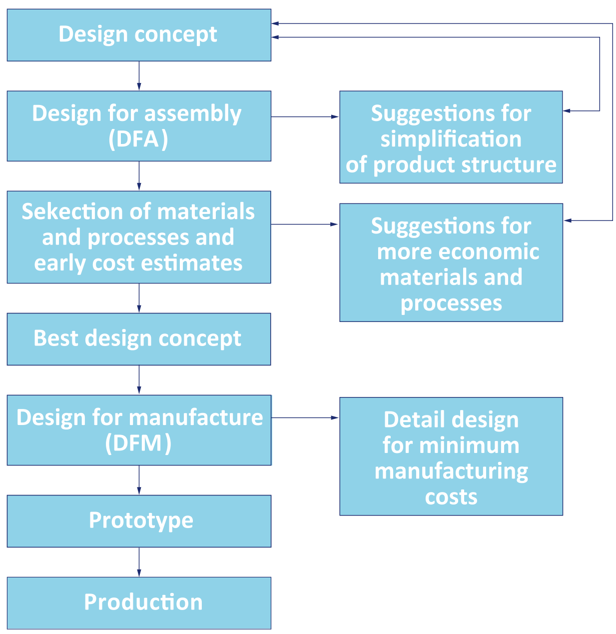


Figure 1.1 Basic concepts and procedures of DfMA (Boothroyd *et al.*, 2011; BESA, 2015)

The key principles of DfMA are minimisation, standardisation, and modularisation to guide design decisions (Gao *et al.*, 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). Table 1.1 shows the general DfMA guidelines and their benefits.

Table 1.1 General DfMA guidelines and their benefits (Bogue, 2012)

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

1.2 DfMA in Construction

In construction, DfMA enables offsite manufacture (OSM) 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 smooth manufacturing significant construction elements in a factory environment (RIBA, 2016; Tan *et al.*, 2020). In essence, DfMA in construction can be interpreted from three perspectives (Gao *et al.*, 2020):

i) a holistic and systematic design process that encompasses how structure or object will be manufactured, assembled and guided with the DfMA principles;

ii) an evaluation system that can work with virtual design and construction (VDC) to assess the efficiency of manufacturing and assembly; and

iii) a game-changing philosophy that embraces the prefabrication and modular construction technologies.

Figure 1.2 Use of virtual reality to rehearse the installation of MEP works (Courtesy of FSE Engineering Group Ltd.)

1.2.1 DfMA Applications and Industrialised Construction

DfMA is one of the key enablers for industrialised construction (IC), offsite and modular techniques (Balfour Beatty, 2018). Also, 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). In general, 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). Figure 1.3 shows the DfMA mindset and its major considerations for the construction industry.

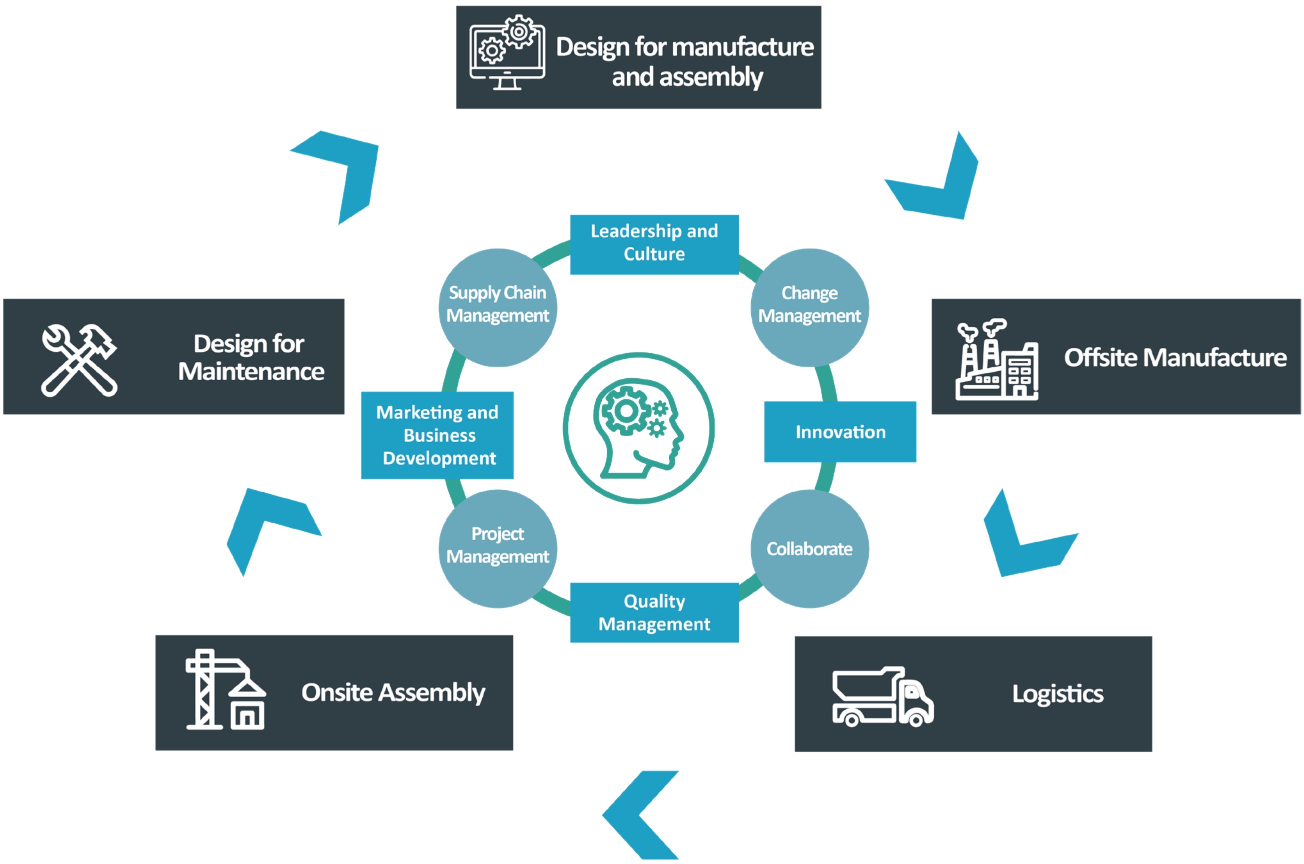


Figure 1.3 DfMA mindset and its major considerations for the construction industry

1.2.2 Degree and Methods of DfMA Adoption

The DfMA approach offers a wide spectrum of solutions in response to project-specific drivers including 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).

Figure 1.4 illustrates three levels of DfMA adoption and their respective requirements. Adoption of the DfMA approach and offsite methods is not a binary choice but a spectrum with different possible combinations (Keung, 2019; Liu, Nzige & Li, 2019).

Figure 1.4 Degree of DfMA adoption

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 1.2 shows different categories of offsite construction (OSC) to be considered when adopting DfMA. Smooth deployment of DfMA principles in construction can be achieved with the support of new project management/delivery methods and Virtual Design and Construction (VDC) technologies (Banks *et al*., 2018; Gbadamosi *et al*., 2019).

Table 1.2 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 system 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)

1.3 DfMA for MEP Works

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; CIC, 2018), little attention has been paid to the adoption of DfMA for MEP systems, particularly the integration with the structural design aspects.

1.3.1 MEP Prefabrication

In practice, the DfMA and prefabrication options for MEP components and systems vary (Drigo & Deadman, 2019; Sands, 2019). Table 1.3 indicates major building services elements suitable for prefabrication. It is important to consider and identify suitable areas for DfMA or prefabrication within the project (ACRA, 2020).

Table 1.3 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 andbusbar trunkings • Conduits and wiring • Power outlets and telecommunication • Electrical switchgear • Emergency generators

Figure 1.5 presents the three design options for prefabricated MEP modules in Singapore. Integrated Assemblies is the design option which the construction industry should pursue.

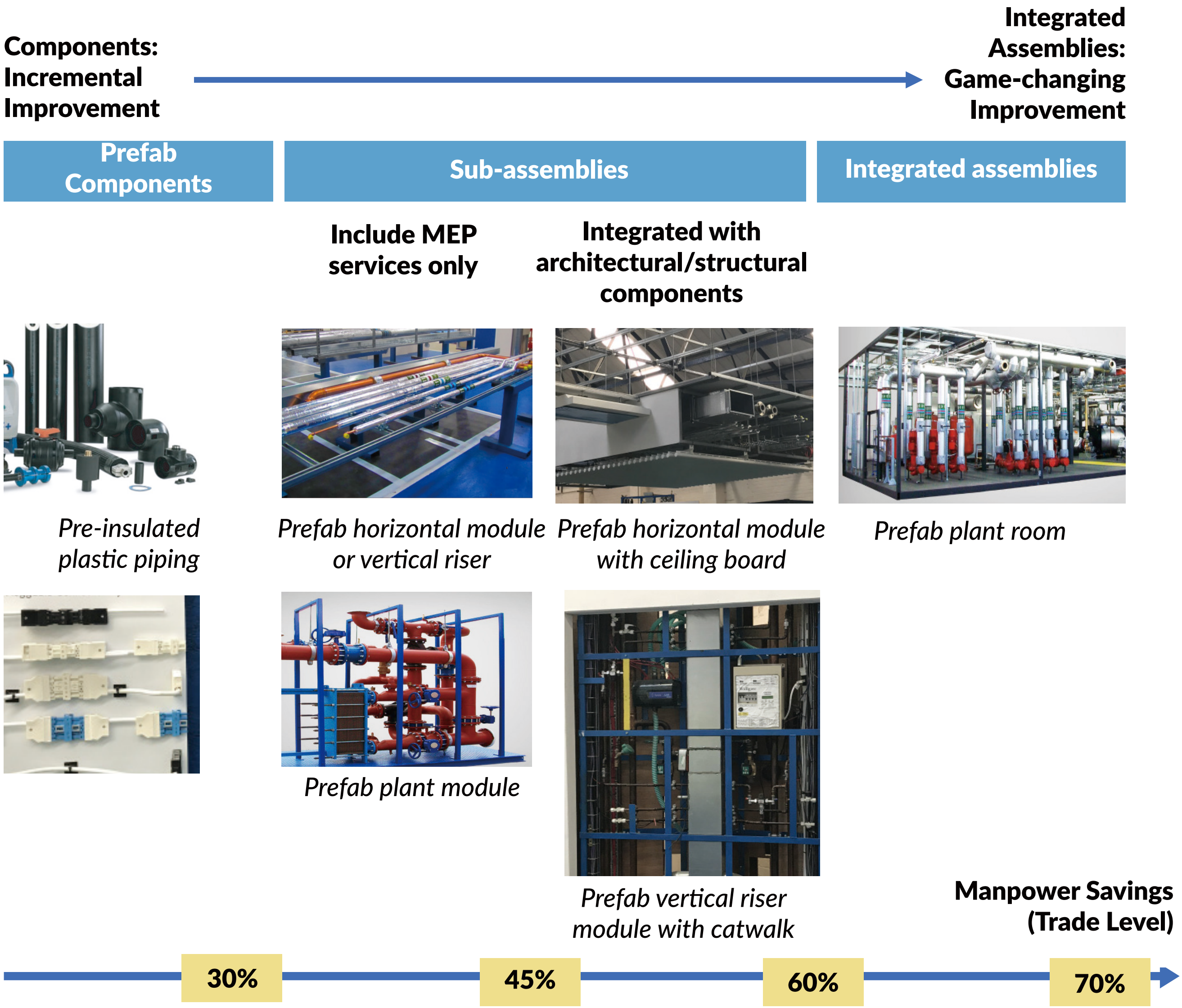
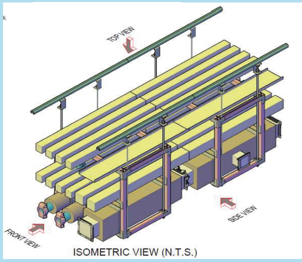


Figure 1.5 Design options for prefabricated MEP modules in Singapore
(Courtesy of the BCA, Singapore)

1.3.2 MiMEP Concept

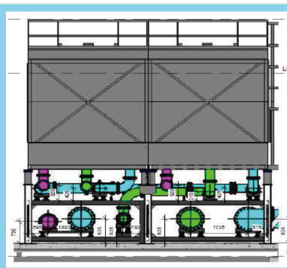
An emerging construction method for MEP works to maximise productivity is known as Multitrade integrated Mechanical, Electrical and Plumbing (MiMEP) for significantly enhancing productivity, work efficiency and quality. Different from the Modular Integrated Construction (MiC) completed with finishes, fixtures and fittings are manufactured in a factory then transported to site for installation (DEVB, 2020; Pan *et al.*, 2020), MiMEP focuses on MEP components/ equipment integrated into modules then delivered to and installed onsite. Figure 1.6 – 1.10 shows examples of MiMEP installation in Hong Kong.

EXAMPLES OF MiMEP VS CONVENTIONAL BS INSTALLATION



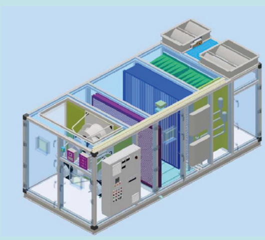
Multi-trade Horizontal Module

- Suitable for building areas with standardized and regular room layout such as open plan office and service corridor
- Components include:
  - Electrical cabling system
  - A/C Terminal box
  - Air ductwork



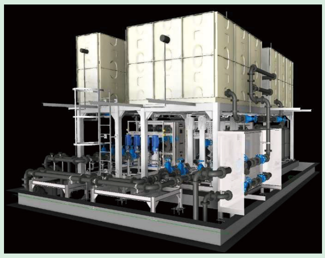
Modular Condensing Pipework for Cooling Tower

- Suitable for all buildings with cooling tower installation
- Components include:
  - Condensing pipes and fittings
  - Valves
  - Vibration isolators



Integrated Air-handling Unit

- Suitable for all buildings with AHU installation
- Components include:
  - AHU
  - LMCP & DDC Panel
  - Chilled water valve set



Pump Room Module

- Pump modules are integrated with structural frameworks and water tanks

Figure 1.6 Examples of MiMEP vs conventional building services installation
(Courtesy of Mr. P. C. Chan of Architectural Services Department)

(a) Pump room modules

(b) Bird's eye view of pump room modules with architectural features

Figure 1.7 Pump room modules with accessories (Courtesy of the Architectural Services Department)

Figure 1.8 Prefabricated plant room modules for a negative pressure isolation ward
(Courtesy of Gammon Construction Limited)

Figure 1.9 MEP prefabrication examples: mechanical ventilation and airconditioning
(Courtesy of FSE Engineering Group Ltd.)

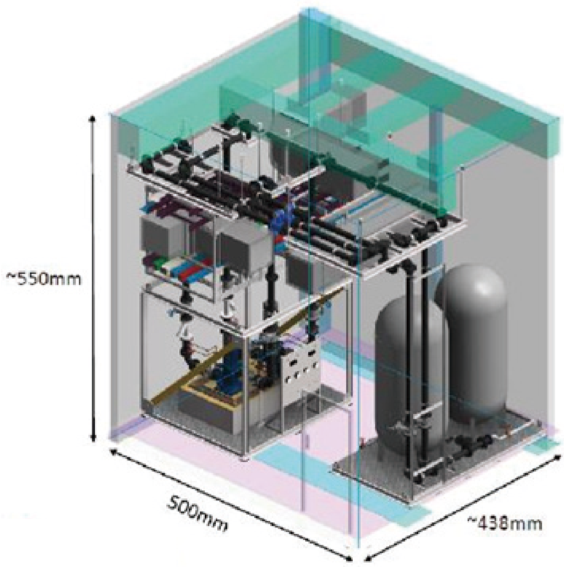


Figure 1.10 MEP prefabrication examples: plumbing and drainage
(Courtesy of Gammon E&M Limited)

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. Three core design principles of MiMEP are:

i) Offsite prefabrication
ii) Multi-trade integration and module maximisation
iii) Plug and play

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 on site (Dwyer, 2019). Completed modules can also be inspected for quality and statutory compliance before transporting to the site.

1.3.3 Important Tasks for MEP Works

When adopting the DfMA approach involving MEP works, it is recommended to make reference to a design framework (i.e. the RIBA Plan of Work as presented in Figure 1.11) to provide guidance on design activities, responsibilities and deliverables across various project development stages.

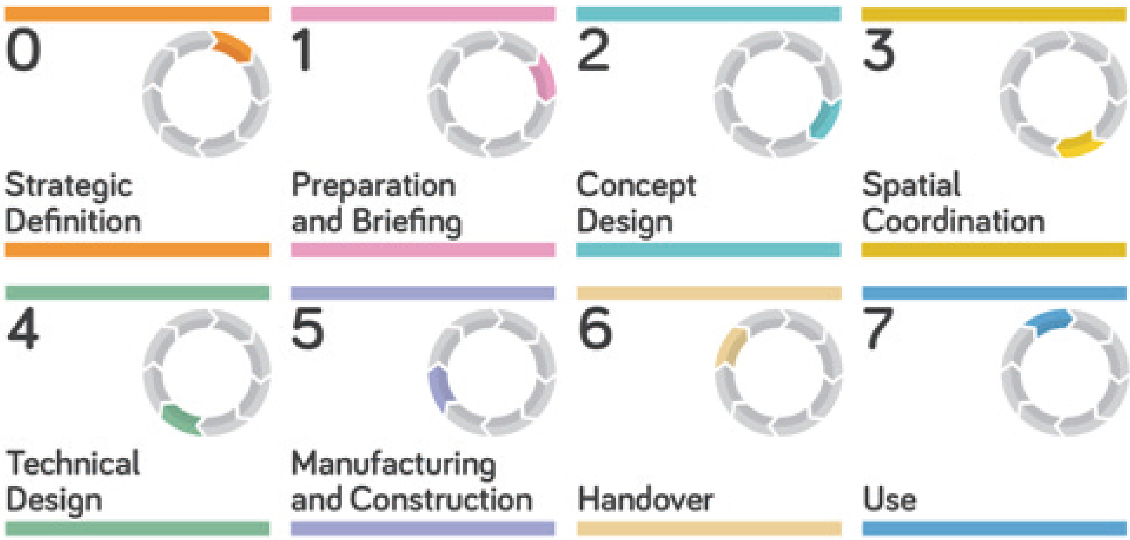


Figure 1.11 RIBA Plan of Work 2020 (RIBA, 2021)

Important tasks involved in the adoption of DfMA for MEP works across various project stages are given in Table 1.4. This Concise Guide provides key considerations and practical strategies focusing on two phases: (a) Planning and Design Development, and (b) Implementation.

Table 1.4 Important tasks for the adoption of DfMA for MEP works

Stage	DfMA Tasks
0 - Strategic Definition	• Consider opportunities of DfMA across portfolios of projects • Consider setting project performance indicators based on client requirements • Set up project team & select procurement method
1 - Preparation & Briefing	• Initiate DfMA thinking • Consider DfMA exemplars & undertake feasibility studies • Consider responsibility matrix of the project team members
2 - Concept Design	• Apply DfMA in the architectural, structural & MEP concepts • Rationalise MEP modules & update procurement strategy • Consider MEP maintenance, tolerance, connections & logistics
3 - Spatial Coordination	• Update construction strategy & cost plan • Develop MEP offsite strategies and detailed design • Consider buildability & multi-trade coordination
4 - Technical Design	• Consider DfMA impacts on MEP systems & interfaces • Develop the DfMA components & specifications • Consider prototyping & evaluate health & safety risks
5 - Manufacturing & Construction	• Update construction strategy & logistics plan • Monitor quality of offsitemanufacturing • Consider commissioning,optimising factory acceptance testing
6 - Handover	• Provide feedback on defects and DfMA process for future projects • Consider MEP system operation & maintenance
7 - Use	• Consider feedback during thein-use stage to informfuture projects • Monitor to enhance asset management & MEP fine-tuning

Notes: (i) Adapted from RIBA (2021) and full version of the Reference Materials.
(ii) Stage 0 to 4: Planning and Design Development
(iii) Stage 5 to 7: Implementation

SECTION 2

PLANNING AND DESIGN DEVELOPMENT

2 Planning and Design Development

DfMA requires robust planning, adapting and optimising the design to leverage offsite fabrication of components and onsite assembly (BCA, 2018). At the early planning stage, it is essential to identify the client's requirements and subsequently to develop project objectives and performance indicators against site and other constraints. Appropriate DfMA strategy and considerations should be initiated at the very onset of the project to maximise the time/cost savings, safety/productivity enhancement and waste reduction. Table 2.1 presents the common performance indicators and constraining factors. Key considerations for adopting DfMA at concept and detailed design stages are shown in Figure 2.1.

Table 2.1 Common project performance indicators and constraints

Performance indicators	Constraints
✓ Cost (minimum construction cost vs. project life cycle cost) ✓ Time (time certainty, design time, onsite construction time, and overall development duration) ✓ Quality (defects, cost of rework, accepted standards, predictability) ✓ Productivity (manpower, materials, machinery) ✓ Design/aesthetics (high profile/iconic vs regular/ repetitive design) ✓ Sustainability (minimising energy and environmental impact, carbon emission) ✓ Health and safety (minimising accidents)	✗ Site constraints (area restriction, access limitation, environment control, transportation/delivery restriction, multi-trade interfaces restriction, availability of workforce) ✗ Process factors (supply chain availability, design change flexibility, standardisation and customisation) ✗ Procurement constraints (project team's experience, early contractor involvement, single-source restriction, lowest cost only, element-specific costing) ✗ Lifecycle costs may not be a priority consideration in 'build-for-sale' projects

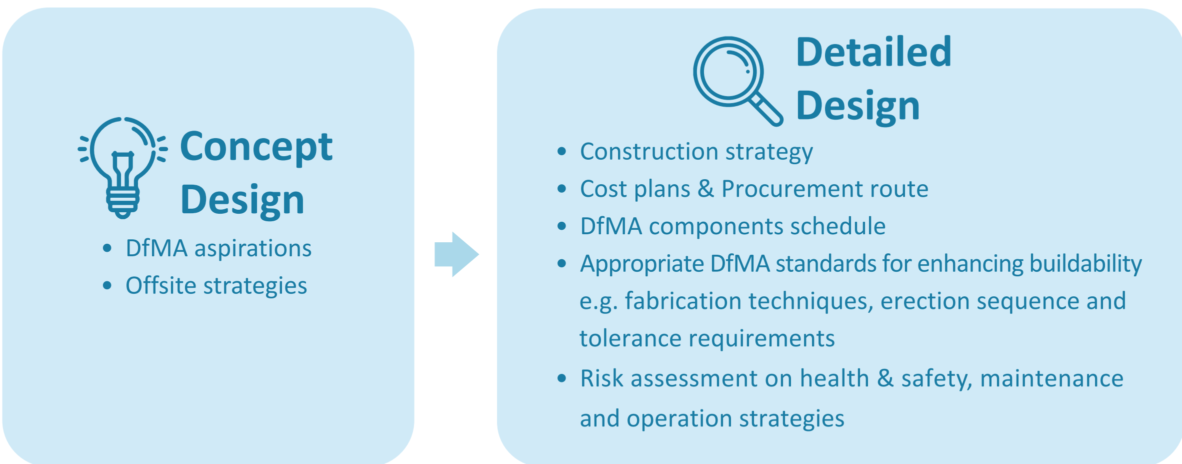


Figure 2.1 Key considerations for adopting DfMA at concept and detailed design stages

2.1 DfMA Strategies

DfMA is both a technical process and a philosophy that should be seen as an evolution of the designer's ordinary way of working (RIBA, 2021). Its benefits are applicable to traditionally built and innovative projects. Opportunities for applying the DfMA should be explored across portfolios or programmes of projects considering their impact on the business case or strategic brief. Very often, DfMA exemplars would be useful and high-level DfMA adoptions (see Figure1.4) should be aimed and tested using the site information and feasibility studies.

2.1.1 Design Options

During project planning, it is important to consider different design options for prefabricated MEP modules (see Figures 1.5 and 2.2) with the help of BIM software, so as to avoid undesirably limited design flexibility, as well as to minimise the difficulties encountered at the construction stage. It is also advisable to identify opportunities to adopt "off the shelf" products or use client-specific standard products or design solutions. Offsite suppliers may have developed their own BIM object libraries for their preferred components and assemblies, such as plant rooms, vertical risers or horizontal service distribution modules for direct adoption and supply chain engagement.

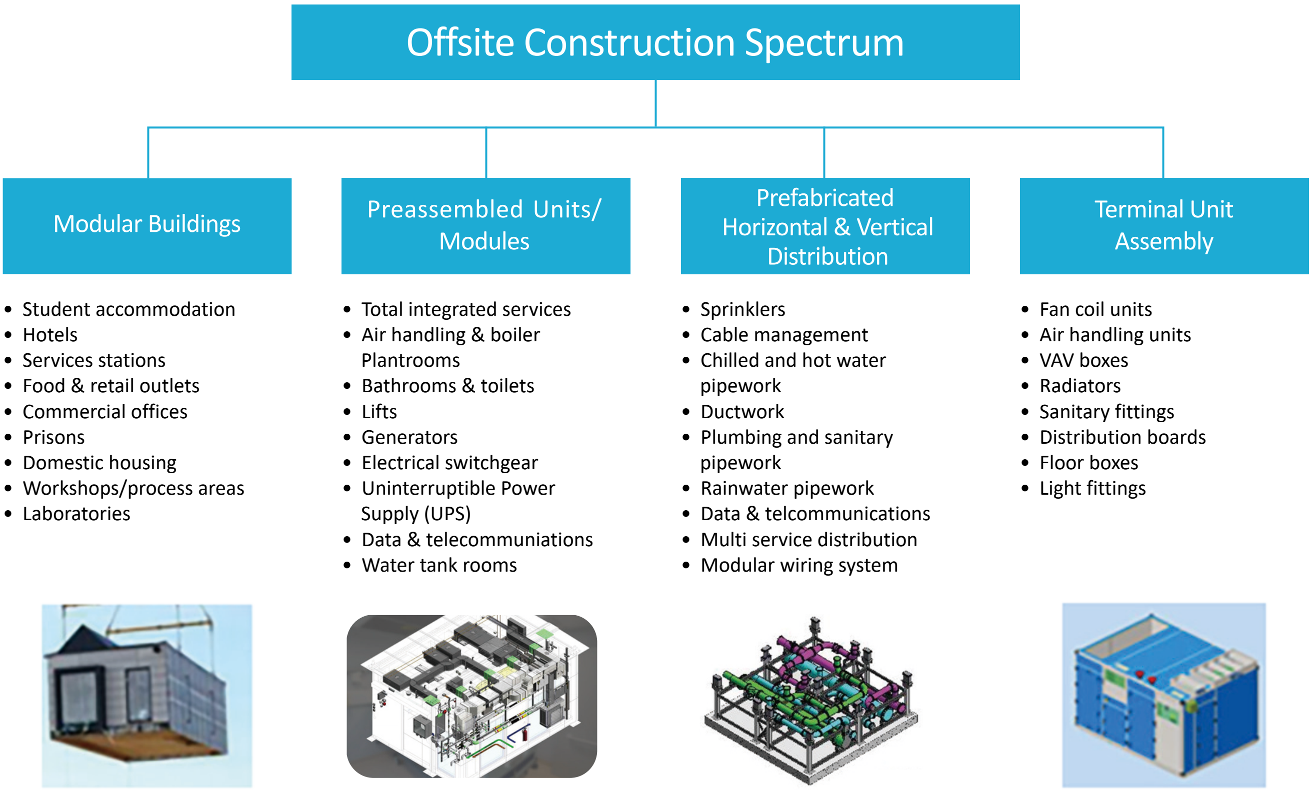


Figure 2.2 Design options for prefabricated MEP modules in the UK (Wilson *et al.*, 1999a)

2.1.2 DfMA and Construction Strategy

It is important to plan in detail for all logistics of the offsite and onsite activities. To seamlessly integrate the offsite manufactured modules with elements constructed onsite, two critical tasks should be included in the brief to ensure they are adequately addressed:

- The management of interfaces between the different work packages;
- A structured approach to the analysis, design, integration, testing and acceptance of the systems;

In developing the construction strategy by the DfMA approach, the project team should leverage on standardised solutions and consider high-level benefits including safety, productivity, quality and sustainability for the greatest impact. Research work might be initiated, if necessary, to integrate DfMA effectively into the concept design to achieve a higher level of pre-manufactured value (PMV).

In fact, innovation is an implied characteristic of DfMA (Langston & Zhang, 2021). It is often necessary to embrace innovative technology to adopt DfMA such as laser scanners for surveying, auto identity/bar codes for logistics and supply chain management, and data analytics for evaluating performance efficiencies.

2.1.3 BIM Tasks

BIM should be used throughout the project lifecycle to enhance the coordination amongst various stakeholders during the design, construction, operation and maintenance (O&M) of the project and management. A project-specific BIM execution plan should be established for the procurement and implementation in the subsequent stages (BSI, 2019a & b).

Key BIM tasks include:

- Develop BIM model and components with DfMA adaptability set out in the design responsibility matrix;
- Validate the BIM model against the client’s requirements;
- Early engage contractor or specialist subcontractor to support the BIM tasks;
- Include MEP systems and the services treatments in the detailed BIM model with relevant information on performance and spatial requirements;
- Set tolerances for detailed BIM models with the client or approval unit and the designer before commencement of detailed design.

2.2 Procurement Tasks

Adoption of DfMA in MEP may require a different approach on procurement. A procurement strategy should be established based on the considerations and objectives set out at the strategic definition stage. The procurement strategy has to include strategies for supervision for both offsite prefabrication and onsite construction.

2.2.1 Early Contractor Involvement (ECI)

Adopting a procurement policy with ECI is expected to be conducive to the success of DfMA application. One example of ECI approach for MEP works is illustrated in Figure 2.3. The process requires early involvement of the MEP subcontractors to work together with the main contractor and the project design consultants. Input from the MEP subcontractors can then be seamlessly incorporated into the design to attain a more effective and holistic technical solution, thereby avoiding late design changes and rework. This can help overcome the contractual break between design and manufacture (Rahman & Alhassan, 2012).

Besides, a leading subcontractor coordinating different MEP services would be desirable. Payment mechanisms and risk allocations need to be tailored to suit procurement of offsite construction under the DfMA approach, so as to reduce purchasing lead time and costs.

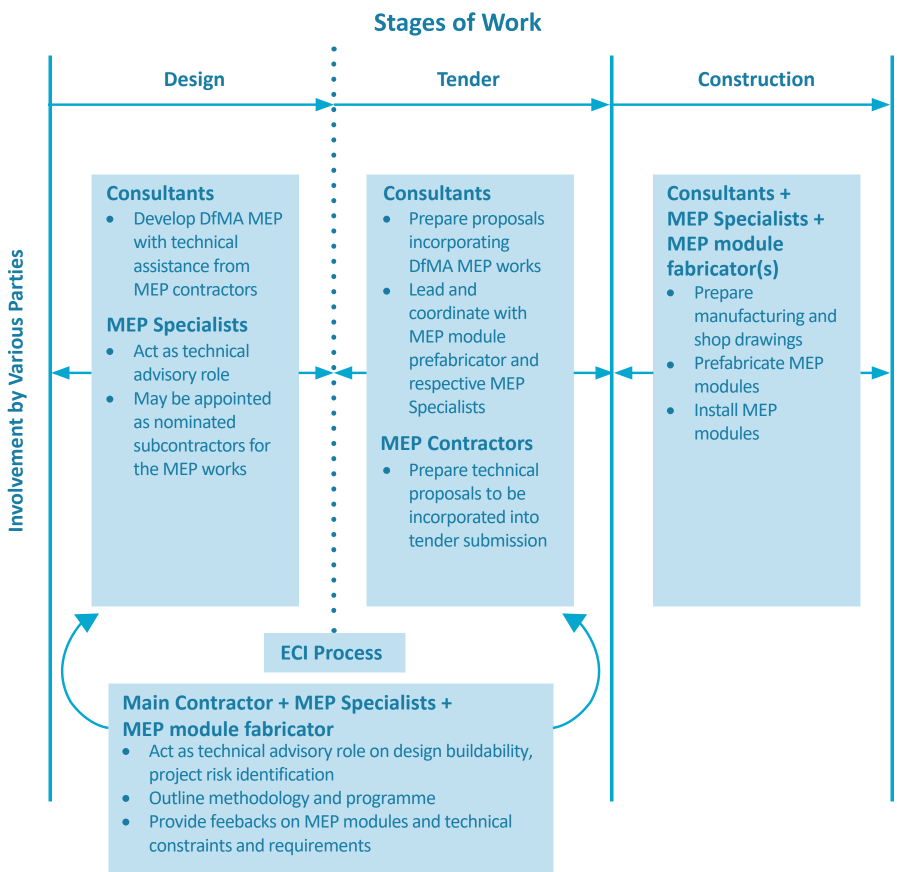


Figure 2.3 ECI approach for DfMA MEP works
[Adapted from Boon & Doig (2019)]

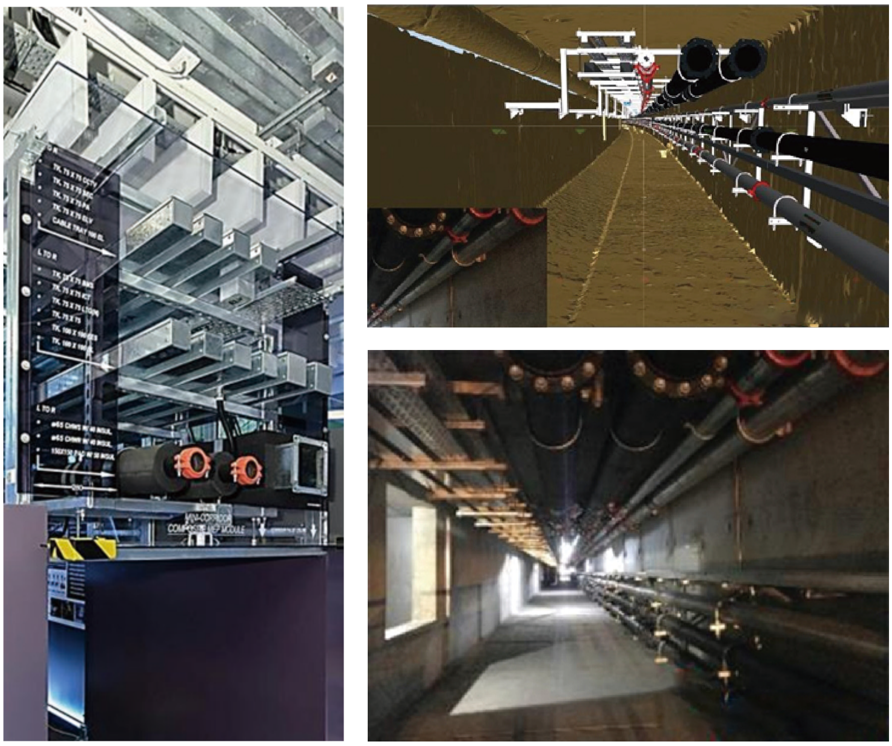


Figure 2.4 Coordination of MEP modules (Courtesy of Gammon Construction Limited)

2.2.2 Collaborative Approach

Project team members are recommended to choose a collaborative procurement model, among the common procurement arrangements shown in Figure 2.5, to maximise the benefits of the DfMA approach. Best value should be considered rather than best price. The procurement strategy should be able to embrace key non-monetary benefits and full lifecycle costing (Trinder, *et al.*, 2018). In practice, the experience with procurement and costing of MiC in Hong Kong could be a useful reference (Ng & Ng, 2019).

With DfMA and OSC, the budget, cash flow and payment certification planning should be as flexible as possible to accommodate alternative procurement routes for offsite options. In particular, the contract terms should allow the MEP specialist subcontractor to claim part of the contract amount for the modules completed in the factory before installation onsite. There will also be potential insurance coverage cost for offsite work-in-progress (WIP) modules.

Traditional approach

- Traditional approach supplementary with buildability adviser during the design stage.

Management contract with an early integrator

- A procurement route in which the works are constructed by a number of different works contractors who are contracted to a management contractor.

Partnering arrangement

- It allows an early involvement and facilitates a less adversarial environment e.g. through adopting relevant NEC practices with early contractor involvement option.

Two-stage tendering

- A contractor to be appointed at an initial stage based on an outline scope of work, enabling early input from related specialist before the final tender and award selection exercise.

Framework Agreement

- With pre-agreed fee and cost framework, qualified suppliers and contractors are allowed timely involvements for well thought solutions.

Design and Build (D&B)

- With the appointment on the main contractor to design and construct the works, D&B facilitates early commitment and a teamwork environment to consider alternative solutions.

Engineering, Procurement & Construction (EPC) contract

- EPC is a type of turnkey contract where the contractor holds the responsibility towards the design, procurement, construction, commissioning and handover of a project.

Integration of Design and Construction

Figure 2.5 Options for contract and procurement arrangement

2.2.3 Quality Standards and Statutory Requirements

Relevant quality standards covering work in manufacturing facilities, the manufacture process and operation of products, and the safety and quality of buildings during construction, occupancy and use must be strictly followed for offsite construction (Liu *et al.*, 2019; Sands, 2019). Wider considerations for adoption of Chinese national standards and other international standards should be fully embedded according to the location of the manufacturers.

The MEP design proposal including product/system/material selection should be in full compliance with relevant statutory requirements and design guidelines (CIC, 2021 &2020). For instance, if a fire-rated duct runs through a MEP module, the entire module frame and associated supports must be fire-rated (see examples in Figure 2.6). If the horizontal ceiling module is used in fire-rated spaces e.g. smoke stop and firefighting lobbies, a fire-resistant board must be incorporated, in accordance with the local statutory requirements.

Figure 2.6 Examples of prefabricated MEP modules (BCA, 2018)

2.3 Design Process

DfMA requires integrating the construction knowhow in the early design stage (Langston & Zhang, 2021). Smooth implementation of DfMA requires the support of new project management and delivery methods (Banks *et al.*, 2018; Gbadamosi *et al.*, 2019).

2.3.1 Project Team and Design Workflow

For effective DfMA implementation, the project team should consider holistically and robustly for the strategic planning and concept development among different disciplines (see Figure 2.7). In addition to the DfMA, it is desirable to embrace lean construction, for example, by minimizing scaffolding, onsite storage, temporary protections, access gridding, craneage and other logistics requirements.

Architectural Design

Selection of DfMA applied areas and demarcate repeating space/ areas for DfMA to maximise standardization yet fulfilling all client's requirements

Structural Design

- Enabling prefabricated MEP modules by optimising the depth of the beams and their strength to support MEP modules
- Defining key MEP spatial requirements and accommodating the space for optimum MEP routing; and
- Formulation of modularisation strategy to address the quantity and complexity of onsite splicing locations between the prefabricated MEP modules and the structural modules

MEP Design

- Involving MEP consultants, main contractor, trade-specific MEP specialist subcontractors, fabricators, installation specialist and maintenance specialist
- Maximising standardisation, modularisation & integration to facilitate DfMA efficiency

Figure 2.7 Important considerations for strategic planning on DfMA adoption

Considering manufacturing lead times and capacity planning, combined with the increased cost of design change at the construction stage, as well as design of offsite elements need to be frozen, prior to manufacturing, planning and ordering the corresponding components and materials. Once the manufacturing procurement process has started and the order received by the supplying factory, the flexibility to change the designs drops rapidly and the cost of change can also increase significantly.

2.3.2 Design and Configuration of MEP Modules

Upfront design coordination of MEP services with structural components and consideration of spatial allowance are the essences of the DfMA approach. Constraints for installation and maintenance should be addressed early to avoid impact on pre-finished works in the later stage. For effective design and configuration of the modules, it is necessary to consider the integrity, expansion flexibility, maintenance, waste minimisation, and impact on structure and fire risk/safety. Practical considerations for MEP modules include:

(a) Supporting frame and interface

- Maximise the use of module frames by including as many services and other non-MEP elements as possible and ensure the cost plan allocation reflects the intended delivery
- Avoid the blockage by supporting frame of the module for free access
- Consider the space and the way to execute connection details to avoid complicated interface

(b) Design of MEP modules

- Establish key protocols for BIM execution across all building lifecycle stages
- Identify potential needs for future expansion/replacement
- Identify any dependencies on the programme, e.g. time for securing watertightness, time and space for moving the modules
- Adopt identical modules as far as possible and minimise unique elements

(c) Maintainability (See Section 2.3.4)

Table 2.2 highlights the recommended design considerations for three main types of prefabricated MEP modules: i) Horizontal ceiling modules; ii) Vertical riser modules and iii) Plant modules.

Table 2.2 Recommended design considerations for prefabricated MEP modules
Horizontal ceiling modules • Aim to include most if not all of the MEP services • Consider the potential risk of undesirable water leakagesand fire safety • Allow at least 100 mm between vertical tiers of the module for access • Allow adjustment to the level to cater for required gradient and construction tolerance
Vertical riser modules • Construct the module comprising ducts and pipeshorizontally at the factory • Install the module prior to the erection of block walls of the riser shaft • Lower the modules into the shaft through designated openings at the top floor • Incorporate lifting lugs and bracketry in the design of vertical riser modules
Plant modules • Fully pre-assemble with control panels, internal wiring and instruments with lifting eyes for piping connection and valves, cable termination for power supply, interfaces for controls and fire alarm system, where applicable • Combine two or more modules using flexible connections onsite

Figures 2.8 shows examples of installation systems supporting the technical equipment for MEP elements such as pipes, conduits and cables. Further information can be found in the relevant European standard (EOTA, 2018).

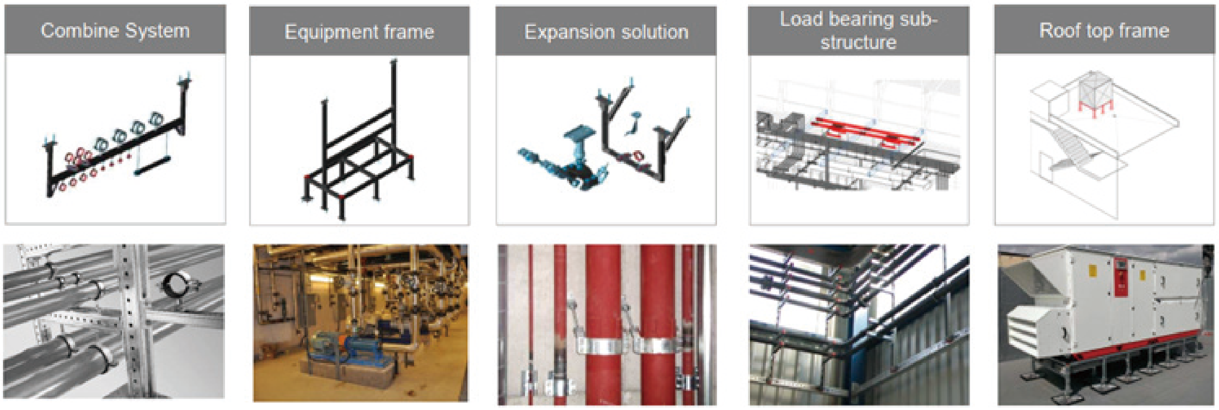
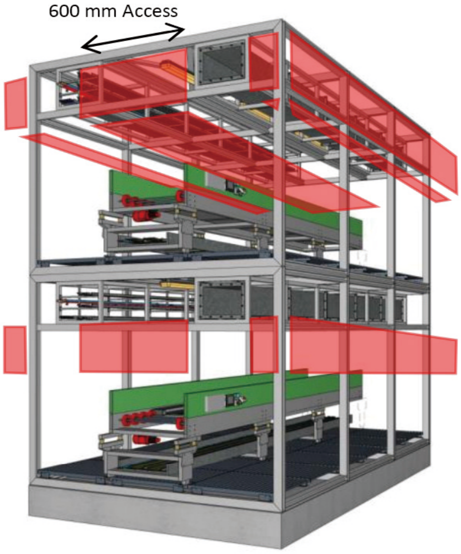


Figure 2.8 Examples of MEP modular installation support systems (Courtesy of Hilti)

2.3.3 Coordination of Design Elements

Coordination of elements designed with DfMA can eliminate duplication and reduce costs. BIM, common data environment and digital data exchange among different contract parties should be covered in the BIM execution plan in Work Stage 0/1 (Inception, Feasibility and Brief Development). The BIM model should be developed sufficiently in the reference design in a D&B contract (or the detailed design in a design-bid-build contract) to ensure that critical information is given to the tenderers during the tendering process.

Early procurement of prototypes/mock-ups can help refine designs before mass production, eliminating or fine-tuning non-buildable elements. Detailed design stage should comprise the design-intent information from the design team and the follow-on development of fabrication information (drawings or models) for approval. Adequate access points, inspection pits and accessible recesses for concealed installations should be indicated on the drawings to facilitate future inspection and maintenance. Adequate space should also be provided at congested positions such as ceiling voids of the corridors (see Figure 2.9 & 2.10 for an example of work access for a horizontal module).



Note: A ‘red zone’ of a minimum width of about 600mm is indicated at the centre of the MEP horizontal module for workers to access both edges of the ceiling modules or install a cat ladder if space is available.

Figure 2.9 Possible configuration of work accesses for horizontal module (Courtesy of AECOM UK)

Figure 2.10 Installation of MEP modules and components onsite
(Courtesy of FSE Engineering Group Ltd.)

2.3.4 Design for Maintenance

Good design practice should consider maintenance of equipment and the repair actions that follow a failure (BCA, 2019), ensuring the ease, accuracy, safety, and economy of maintenance tasks. It requires timely integration of design and construction knowledge with operations and maintenance experiences into the project design at an early stage. Figure 2.11 shows the design philosophy of services allocation with maintenance access.

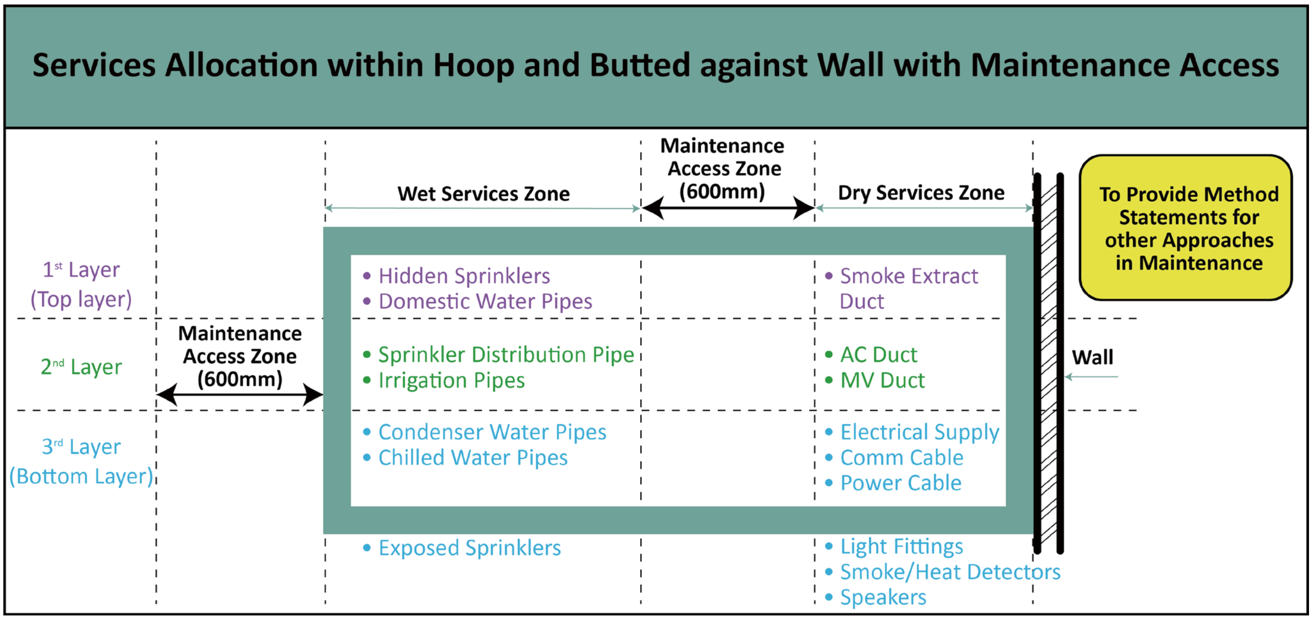
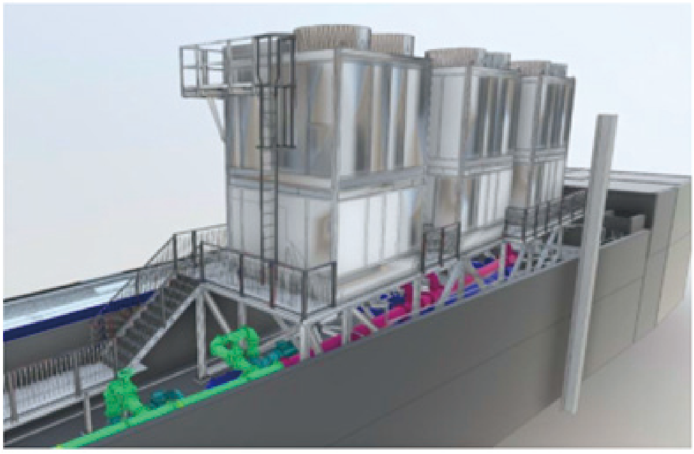


Figure 2.11 Allocation of MEP services within a horizontal module with maintenance access
(Courtesy of BCA Academy, Singapore)

For most MEP systems, the major considerations and design factors of maintainability include:

- Provision of sufficient working space for maintenance work, including inspection, repair and replacement of components or equipment;
- Provision of adequate access and appropriate facilities (e.g. working platform) for carrying out required maintenance work (See Figure 2.12);
- Avoidance of maintenance work at height or in confined spaces and minimising maintenance interventions and inconvenience to the building occupants; and
- Provision of appropriate means and methodology for replacement of any modular MEP plant (e.g. the AHUs) and associated components.

(a) As-fitted module



(b) BIM Model

Figure 2.12 Prefabricated cooling tower modules with maintenance access provisions
(Courtesy of Jardine Engineering Corporation)

SECTION 3
IMPLEMENTATION

3 Implementation

Deployment of the DfMA principles in construction requires the support of new project management/ delivery methods and digitalised design and construction technologies. It is important to manage the project information process, logistics and tracking, vertical transport/hoisting, and quality management (Blake & Sands, 2021; Kuzmanovska & Aitchison, 2019).

3.1 Project Administration and Management

As various design options require inputs across the construction value chain, the client should allow adequate time for design using BIM software and collaboration among consultants, main contractors, MEP specialist subcontractors and prefabricator. Suitable terms and standard forms of building contract should be used to facilitate smooth project administration.

Once prefabrication is completed, any design changes or re-routing would cause widespread disruptions. Hence, it is desirable to confirm and freeze the designs including the combined/ coordinated services drawings (CSD) of MEP services early. Clients are also encouraged to require the main contractor and MEP specialist subcontractors to provide more detailed BIM drawings to facilitate offsite prefabrication of MEP modules, quality assurance, and lean construction.

3.1.1 Method Statements and Tolerances

Manufacturing method statements should be compiled bringing all relevant and detailed information at the production stage using visual set of instructions for assembling a particular product or family of products. Risk assessment and health and safety strategies should be updated to consider manufacturing and assembly risks (Enshassi *et al*., 2019). BIM model is instrumental for preparing method statements, risk assessment, animating assembly sequences, and swift information retrieval.

Tolerances for detailed design models in relation to volume, area, length, weight or other properties, should be agreed between the client or approval unit and the designer before commencement of detailed design. Tolerances for technical design and as-built models should also be agreed between the recipient and the author before the technical design starts. Figure 3.1 indicates types of tolerances in construction and MEP elements.

Designers should master the tolerances and fixing systems for different product families, materials and production methods. Where a predictable dimensional range and tolerance of an offsite assembly is determined, a fixing system for accommodating the two extremes of these ranges may be used. With a good control over both the structural element and the related MEP element, fixings may be pre-positioned and incorporated into the structure during manufacture.

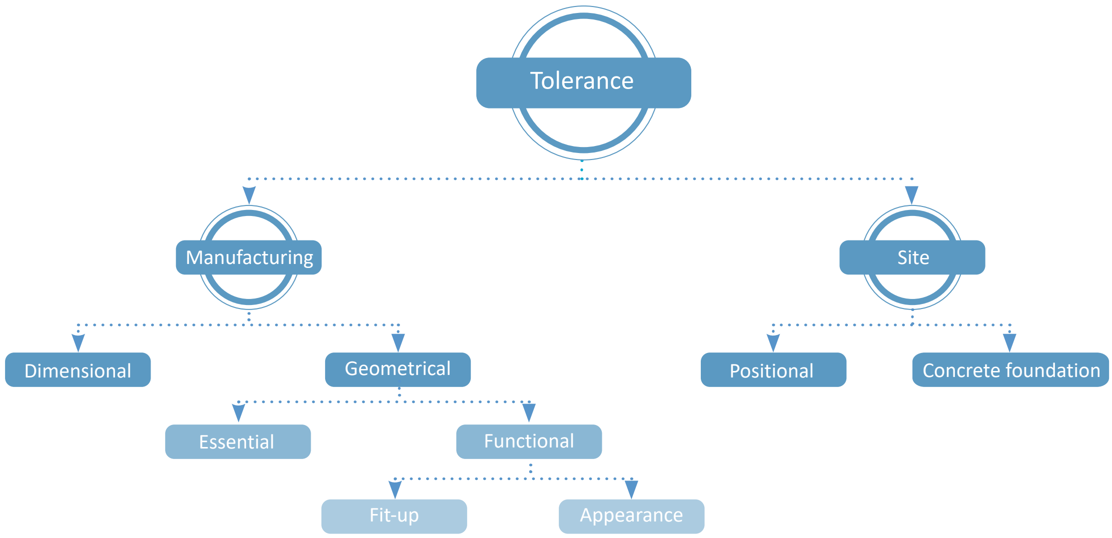


Figure 3.1 Types of tolerances in construction and MEP elements (Enshassi *et al*., 2019)

3.1.2 Lean Construction and Management

During the construction stage, the offsite and onsite activities should be seamlessly dovetailed by the application of lean construction methods to create a smooth workflow, with less waste, greater predictability, lower cost and a focus upon continuous improvement. Project stakeholders should communicate and collaborate closely to determine the schedule of tasks.

Lean manufacturing tools such as value stream mapping (VSM) would be useful to categorise various items and optimise the management of offsite manufacturing elements. Material- and information-flow mapping allows managers to improve the process by visualising both its value-adding and wasteful steps. An example of VSM is shown in Figure 3.2.

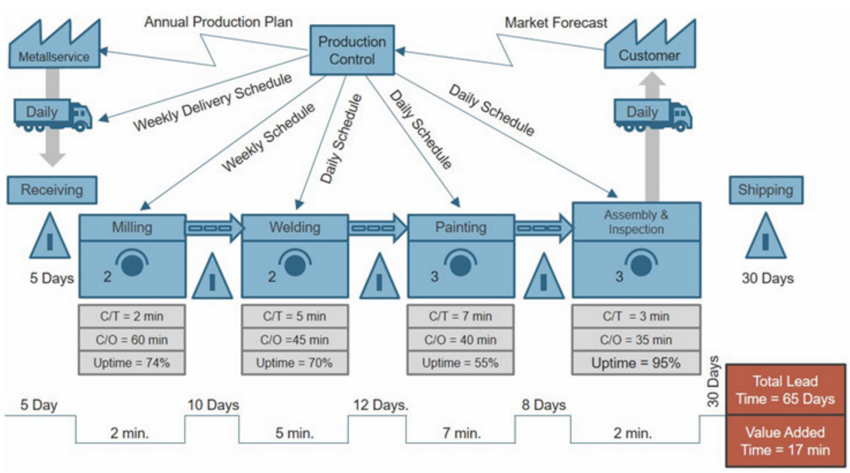


Figure 3.2 An example of VSM for lean manufacturing

3.1.3 Design for Assembly and Offsite Manufacturing

DfMA components should be accurately developed by considering the implications of possible methods of manufacturing or fabrication. More details should be developed on the interfaces and specifications for structural, water/moisture/vapour penetration, and vibration/acoustic issues. Four key propositions of DFM are recommended when OSC is applied for MEP works as shown in Table 3.1.

Table 3.1 Four key principles of DFM for MEP works (BESA, 2015)

Proposition	Description
Design for productivity	• Determine the required site installation rate and prepare the design to optimise the manufacturing process • Design the layout of the offsite facility to match the required rate of output from the assembly facility • Establish a mechanism to trigger assembly on a need and timely basis • Design the facility elements for logistics and productivity • Use in-process inspection and acceptance at factory • Use simple visual inspection of material and tooling locations that can be easily understood by all personnel working in the area
Design for modularisation	• Consider adopting six modularity types (component sharing, component swapping, cut-to-fit, mix, bus & sectional) • Standardised components should give benefits to lead time, stock levels, repeatability of process (thus quality) but still allows customisation within pre-defined parameters
Design for manufacturability	• Early engagethe manufacturers to advise on ease of manufacturing components to maximise the offsite benefits • Incorporate the capacity and capability of the manufacturer into design considerations
Use common parts & materials	• Use configuration management in association with a defined numbering system to control and optimise the number of parts, thereby reaping the benefits of multiple repeated usage

3.1.4 Progress, Scheduling and Quality Assurance

Project progress and production scheduling should reflect the site delivery requirements in order not to lose efficiencies gained in the factory. The batch size and production schedule should be flexibly designed to be more responsive to changes to the construction sequence onsite. All suppliers should have a robust, quality assurance process in place for the delivery of components with critical dimensions in particular. The six sigma concept (Figure 3.3) should be applied for getting the outputs right first time every time.

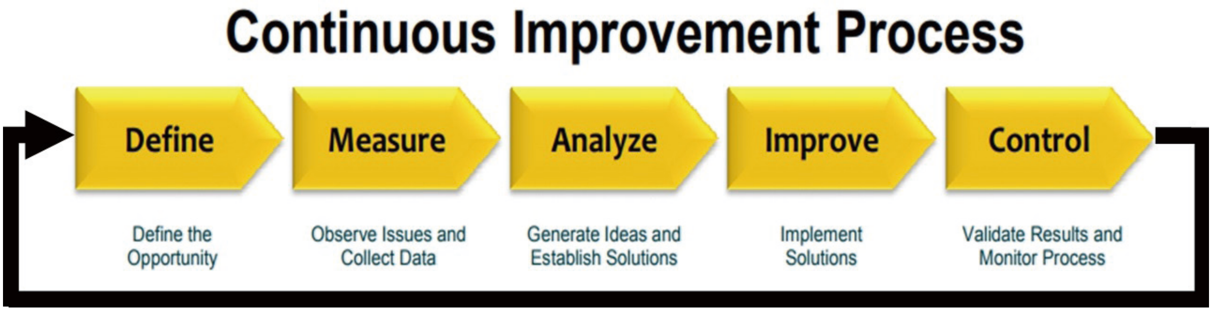


Figure 3.3 Lean six sigma (6σ) concept (Courtesy of AECOM)

Once the MEP modules have been produced in the factory, the manufacturing drawing should be shown on the respective modules and the services accordingly. Geographic information system (GIS) and global positioning system (GPS) devices or radio frequency identification (RFID) can also be used to track the modules and facilitate installation onsite (see Figure 3.4 for an example).

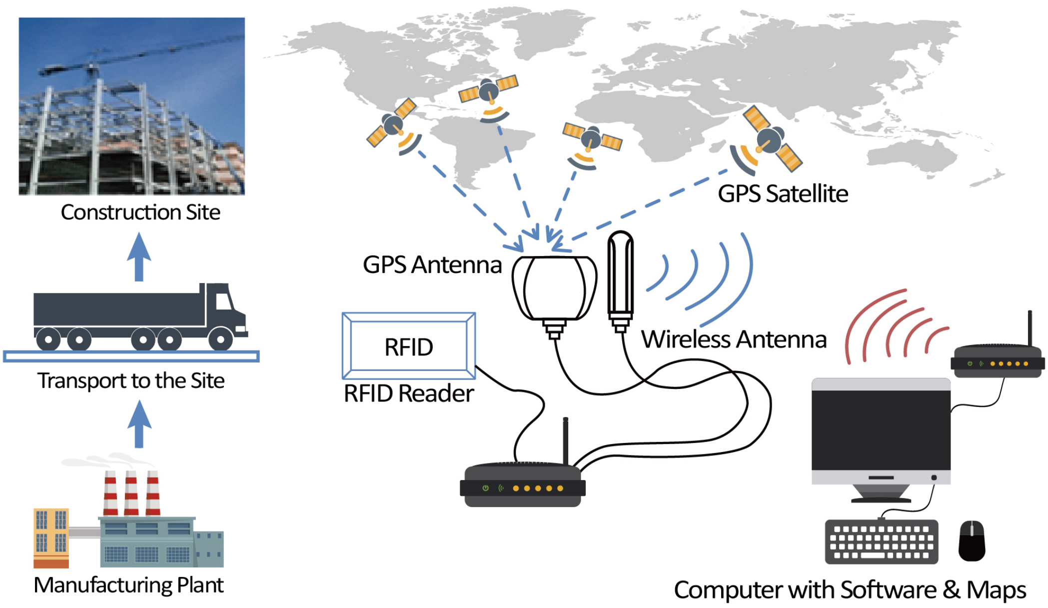


Figure 3.4 Tracking system using RFID with GIS and GPS support (Sardroud *et al.*, 2010)

3.1.5 Inspection, Commissioning and Approval

Upfront material and commissioning planning is critical for prefabricating MEP modules. Clients need to approve relevant materials early for expediting prefabrication process. Mock-ups of typical MEP modules should be produced for the client's approval prior to mass production. It is important to monitor quality of prefabricated products and consider commissioning to optimise the use of factory for acceptance testing.

To ensure a smooth installation of MEP modules onsite, the tender should require training and competent assessment for workers to carry out the safety- and quality-critical tasks in the factory, and to rectify defects of modules installed onsite. An independent Engineer's Representative should be engaged to inspect/check/audit the critical elements of works done in the factory. For factories outside Hong Kong, independent inspection in another jurisdiction may be needed to support modules payment.

3.1.6 Lead Coordinator and Work Sequence

Figure 3.5 shows an example of parties involved in technical works of MEP modules. Under the DfMA approach, a lead party preferably the main contractor or an MEP specialist subcontractor is recommended to coordinate logistics and onsite activities. With a different work sequence, the payment certification, bill of quantity and schedule of works in the case of a lump sum contract will have to be tailored accordingly. To facilitate offsite payment, the standard conditions of contract may need to be amended.

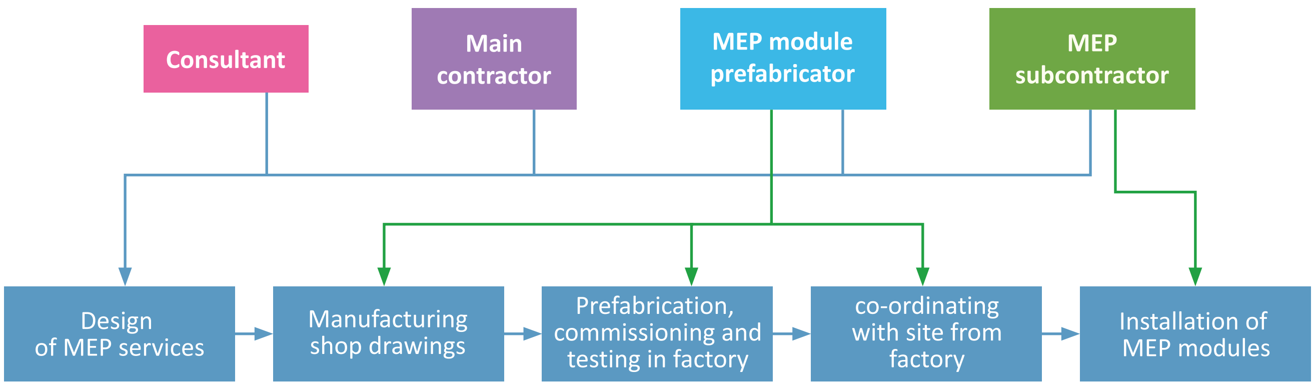


Figure 3.5 Parties involved in the technical works of MEP modules (BCA, 2018)

3.1.7 Payment Model and Arrangement

The payment model should address the payment method for materials and/or works in the factory, such that payment shall be paid to the MEP contractor at the following stages, with due consideration of the contract and stipulated specification:

- Preliminary cost to the consolidation of design details
- Materials delivery to factory and at buffer storage
- Finished DfMA modules in ex-stock/factory storage or onsite
- Work done after the module installation is completed onsite

Offsite work progress payment is important to encourage offsite work. Payment shall be aligned for the correct delivery of the right quality items at the planned time. The following approach should be considered when designing the payment arrangement for offsite work:

- Payment for completed modules, not materials
- Liability for completed modules belong to the owner after handover
- Payment for completed modules
- No payment for immature completed modules not meeting the minimum level of completeness specified

3.2 Construction Process and Logistics

During the construction stage, logistics arrangement and construction process of installing MEP services would be distinctive under the DfMA approach. The construction strategy should therefore be updated by considering the logistics arrangement (lifting, handling and transportation) and programme for each DfMA component and subassembly.

It is useful to store constructed DfMA information in a BIM object library. Lessons learned should be archived for continuous improvement. Especially the performance of specialist subcontractors and manufacturers involved in the DfMA deliverables should be adequately evaluated.

3.2.1 Logistics Considerations

Logistics can have significant impacts on the concept design and modularisation strategy. Project team should evaluate the logistics between the factory and the site, as well as the sequence of manufacture and assembly (RIBA, 2021), using swept path and logistics analysis in conjunction with the BIM site model to establish the delivery route and the tentative delivery programme.

The maximum size, extent of modularisation, services strategy, materials specifications, etc. will be influenced by several factors such as the length of each module. If the MEP modules fall outside the permitted geometrical parameters, a Wide Load Permit (WLP) is required under local regulatory requirements. Table 3.2 summarises the essential logistics factors. Figure 3.6 shows examples to illustrate the module size limit due to transportation truck and lifting frame used during module placement.

Figure 3.6 Module size limit due to truck and lifting frame used during module placement (Liew *et al.*, 2019)

Table 3.2 Essential logistics factors for MEP works by DfMA

Factor	Description
Road transport	Avoid difficulty and high cost for transportation against the road traffic control application, environmental control on noisy work, etc.
Craneage & lift	Consider site constraints, access, lifting and oversailing of adjacent obstacles for all lifting and installation works in congested areas. See Figure 3.6.
Site constraints	Set up suitable site access for low loaders, turning circles, radii for large vehicles. Establish predetermined delivery routes within the site. Arrange necessary parking space.
Manufacturer constraints	Assess the flexibility for movement in the manufacturing space. Plan delivery routes from factory to site and delivery schedule.
Construction programme and sequence	Fully share the usage of facilities for handling structure, façade and other architectural elements by combining module elements. Early determine the cast-in details and openings.
Component supply	Early assess and schedule component supply with long lead time on the pre-construction programming.

Note: More detailed information can be found in CIC (2021).

3.2.2 Obligation of the Main Contractor

Very often cooperation of the main contractor is essential to the successful implementation of the DfMA approach. The key areas of consideration for the DfMA modules include:

- Provision of builder's works including plinths, principal datum and setting out
- Provision of left-out walls and/or slab openings for delivery of the modules
- Provision of tower crane for lifting & positioning
- Provision of hoisting facilities including cast-in U bolt, cast-in lifting eye bracket, steel channel or I-beam for lifting, loading and unloading, installation, and future maintenance or replacement works

The main contractor should coordinate with nominated subcontractors and specialist contractors on the provision for logistics (such as tower cranes, hoists, loading and unloading platforms, access, temporary openings, etc.) and for the storage of offsite prefabricated components throughout the construction period, with the following essentials:

- Allocation of a small works area onsite for handling the MEP modules and their assembly installation works.
- Close collaboration between the onsite project manager and offsite factory manager to minimise the conflict among trades.
- Application of lean construction principles and suitable procurement strategy to capitalise on offsite manufacture and supply.

3.2.3 Delivery to Site

Before the delivery of MEP modules to a construction site, it is recommended to carry out the following preparation work:

- Use a template or jig when lining up the modules in the factory to check for proper alignment (see Figure 3.7) to ensure smooth installation onsite.
- Cover modules with shrink wrap, tarp, etc. or keep in sheltered condition for protection against exposure to weather.
- Pre-install modules with castor wheels that can be taken off after installation. Use pallet jacks and forklifts to facilitate the manoeuvring and lifting of modules.
- Integrate structural works into the MEP modules to facilitate the installation of MEP modules in tight working spaces (see Figure 3.8).

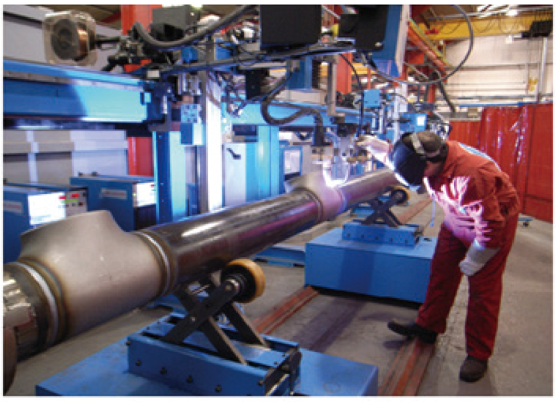


Figure 3.7 Jig for welding pipes
(Courtesy of Laing O'Rourke)

Figure 3.8 Horizontal module integrated with partition wall
(Courtesy of BYME Engineering (H.K.) Ltd.)

3.2.4 Just in Time (JIT) Concept

It is recommended to implement the just-in-time (JIT) concept particularly for delivering large MEP modules according to the construction sequence to streamline onsite operations. BIM can be used to simulate the installation procedures and identify potential logistic issues. Close coordination among both onsite and offsite parties is critical. An example of prefabrication and JIT delivery on construction site is shown in Figure 3.9.

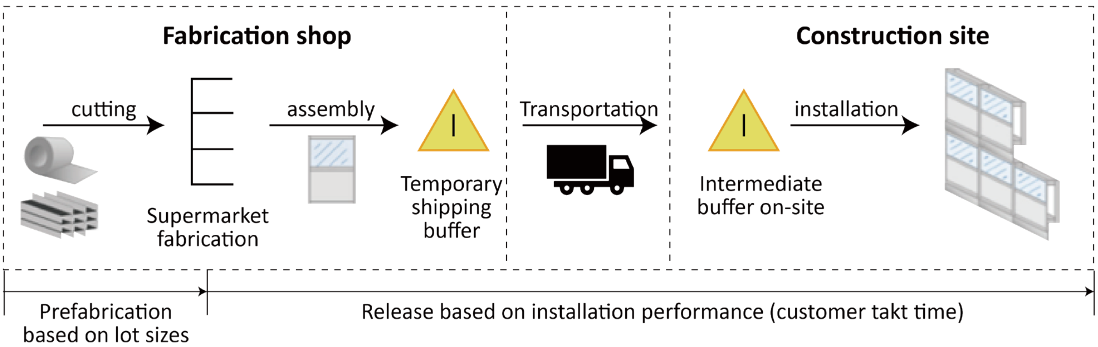


Figure 3.9 Prefabrication and Just-in-Time delivery at construction site (Matt *et al.*, 2015)

In general, best practices for a smooth JIT operation are as follows:

- Deploy tracking systems such as GPS on prime movers.
- Allow space for unloading and storage when JIT installation is not feasible.
- Employ traffic controller(s) to ensure smooth traffic management within the site.
- Establish proper workflow for prefabricated MEP modules with steps indicated (see Figure 3.10).
- Apply the essential logistics factors as presented in Table 3.2 and apply feasible solutions.

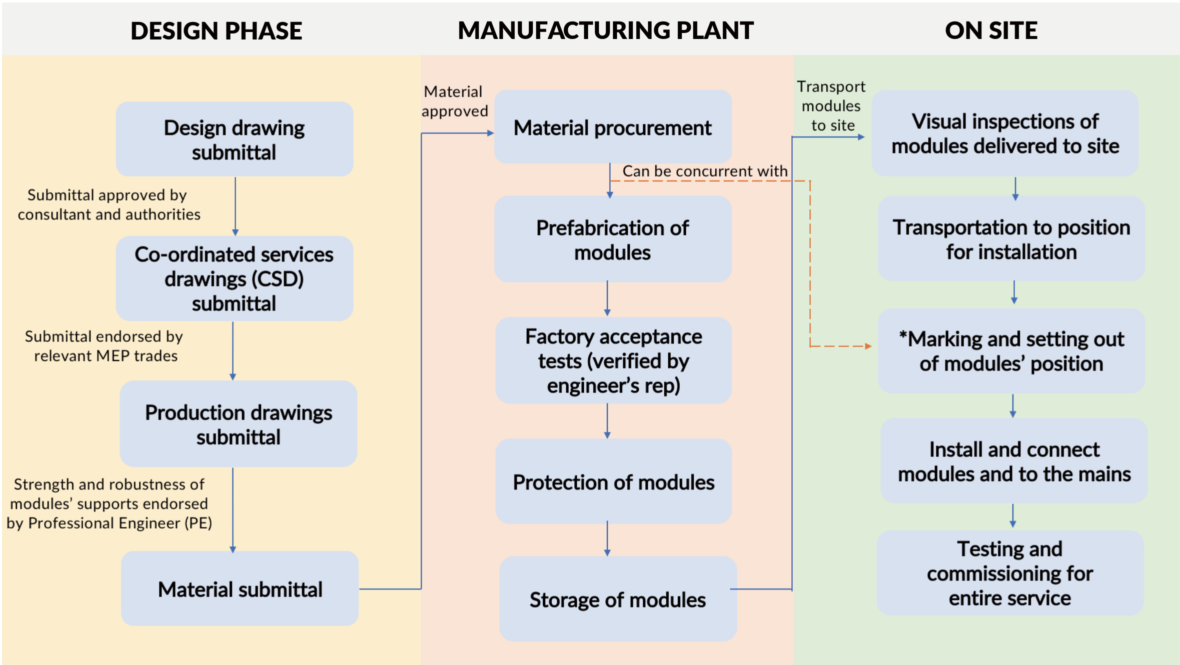


Figure 3.10 Workflow for prefabricated MEP modules (BCA, 2018)

3.2.5 Lifting and Positioning

The craneage, hoist and module lifting strategy should be developed as part of the early construction advice input. Centres of gravity can be calculated in BIM with lifting fixtures positioned accordingly. Safety considerations should be designed into the lifting system with repeatable and capable processes. For example, a scissor lift can be positioned under an assembling, transporting and installation frame (ATIF) for lifting modules (Figure 3.11).

(a) in BIM model

(b) in reality

Figure 3.11 Assembling, transporting and installation frame (ATIF) (Courtesy of Crown House Engineering)

Best practices for lifting and positioning MEP modules are as follows:

- Incorporate positioning guides (e.g. cones or tapered components) in the design.
- Embed adjustable fine-tuning screws into the lifting system for precise control.
- Adopt the floor plate capable to receive modules with their own floor (e.g. bathroom pods).
- Compile clear methods statement for each type of lifting/hoisting operation (see Figure 3.12 for two examples of module lifting).
- Configure the crane to handle large modules and covering the intended block.

Figure 3.12 Lifting of MEP modules for installation

3.3 Handover and Operation

The entire lifecycle of a project with the lean and BIM workflows is shown in Figure 3.13. Upon satisfactory completion, priorities would be facilitating the successful handover of the building. The project team should conclude all aspects of the building contract, including the inspection of rectified defects, acquisition of required certificates, etc. according to the procurement/handover strategies and project-specific schedules.

Crucial at this stage is compiling the 'as-constructed' information with the support of BIM and other digital technologies for effective building operation and maintenance. This might incorporate a wide range of DfMA information, including how the MEP systems and the building might be disassembled, which requires early contractual planning and agreement by the client.

Figure 3.13 Project lifecycle with the lean and BIM workflows (Koseoglu *et al.*, 2018)

3.3.1 MEP Systems Operation and Maintenance

The followings highlight the best practices for smooth operation and maintenance of various MEP system:

- Design each MEP system both individually as well as at the interfaces so that each system or each component can be replaced on an individual basis.
- Consider different design life of the MEP modules and how these can be safely and efficiently decommissioned and disassembled/replaced.
- Allow reasonable physical access for removal of large components for replacement with detailed information on safe disassembly and removal of items and systems as part of the O&M manuals and/or BIM model (BSI, 2020a & b).
- Early determine responsible parties to compile, coordinate and communicate relevant handover information, with adequate budget cost and necessary resources.

3.3.2 As-built Information and Feedbacks

To enhance asset management, relevant technical documents, drawings, approved building plans, reports, T&C records, inspection records and certificates of MEP systems and DfMA products should be incorporated into the BIM model and managed by the facility management team of the building. Configuration management techniques are also desirable to maintain an updated record of the building.

All relevant documents relating to the DfMA components or modules (e.g. approved as-built general building plans (GBPs) and fire service installation (FSI) drawings, design calculations for FSI should be linked to the BIM model for feedback and MEP fine-tuning. The established BIM model and associated digital technologies would be useful to support the O&M of the MEP systems such as monitoring of the performance of the components, monitoring disassembly and updating of the records of the various installations.

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Appendix 1 – Terminology

Term	Definition
Assembly (noun)	An item formed by aggregating or combining different components or elements in part (sub-assembly) or in full (assembly).
Assembly (verb)	The act of construction of a building through the combining and securing of manufactured components onsite, generally in a planned, tested and carefully controlled sequence.
Buildability/ Constructability	It is a project management technique to review construction processes from start to finish during pre-construction phase. It is to identify obstacles before a project is actually built to reduce or prevent errors, delays, and cost overruns.
Component	Manufactured individual building element including prefabricated elements.
Design for Assembly (DFA)	Design of parts and products for easy assembly. Product design aimed specifically at simplifying a product and its overall assembly.
Design for Manufacture/ Manufacturability (DFM)	In a broad sense, DFM includes any step, method, or system for providing a product design that eases the task of manufacturing and lowers manufacturing cost. In a more specific sense, DFM is primarily a knowledge-based technique that invokes a series of guidelines, principles, recommendations, or rules of thumb for designing a product which is easy to make.
Fabrication	A manufacturing process, generally taking place at a specialised facility, in which various materials are joined to form a component part of the final installation.
Industrialized Construction (IC)	Approach that promotes the advancement of construction processesby employing mechanization and automation. It is a construction system that uses more innovative and integrated techniques that connect the design-to-make process.
Lean construction	It is a combination of operational research and practical development in design and construction with an adaption of lean manufacturing principles and practices to the end-to-end design and construction process. Unlike manufacturing, construction is a project-based production process.
Manufacturing	The production of a building element (components, assemblies or modules) in a commoditised manner, typically in a factory environment located remotely to the construction site.
Mass customisation	The benefits of mass production are creatively combined with systems that offer greater choice for the individual customer, improved control of the total construction process, and flexibility of assembly options.
Modular integrated Construction (MiC)	An innovative construction method whereby free-standing integrated modules (completed with finishes, fixtures and fittings) are manufactured in a prefabrication factory and then transported to site for installation in a building.
Multitrade integrated Mechanical, Electrical and Plumbing (MiMEP)	A construction method whereby Mechanical, Electrical and Plumbing (MEP) components and equipment are integrated into a subassembly offsite and then deliver to and installed onsite.

Offsite	Manufacture and pre-assembly of components, elements or modules before installation into the final location.
Offsite Construction (OSC)/ Offsite Manufacturing (OSM)	Largely interchangeable terms referring to the part of theconstruction process that is carried out away from the building site. This can be in a factory or sometimes in specially-created temporary production facilities close to the construction site (or field/flying factories).
Preassembly	The manufacture and assembly of a complex unit comprising several components prior to the unit's installation onsite.
Prefabrication (Prefab)	It is the offsite construction of building elements and assemblies in a factory, which are then transported to a site for assembly and installation.
Standardisation	The use of modules, assemblies, components, interfaces, methods or processes that are repeated through a project and from project to project. Standardisation benefits from the use of continuous improvement processes.
Sub assembly	An assembly of components brought together at either site or in a factory to form completed systems or volumetric assemblies.
Supply chain	Everyone involved in the design, construction and, potentially, maintenance of a building, including the design team, contractor, subcontractors (including specialist subcontractors) and suppliers of materials and other aspects.
Volumetric preassembly	Units that enclose useable space, but do not of themselves constitute the whole building. Examples are toilet pods, plant room units, modular lift shifts, etc