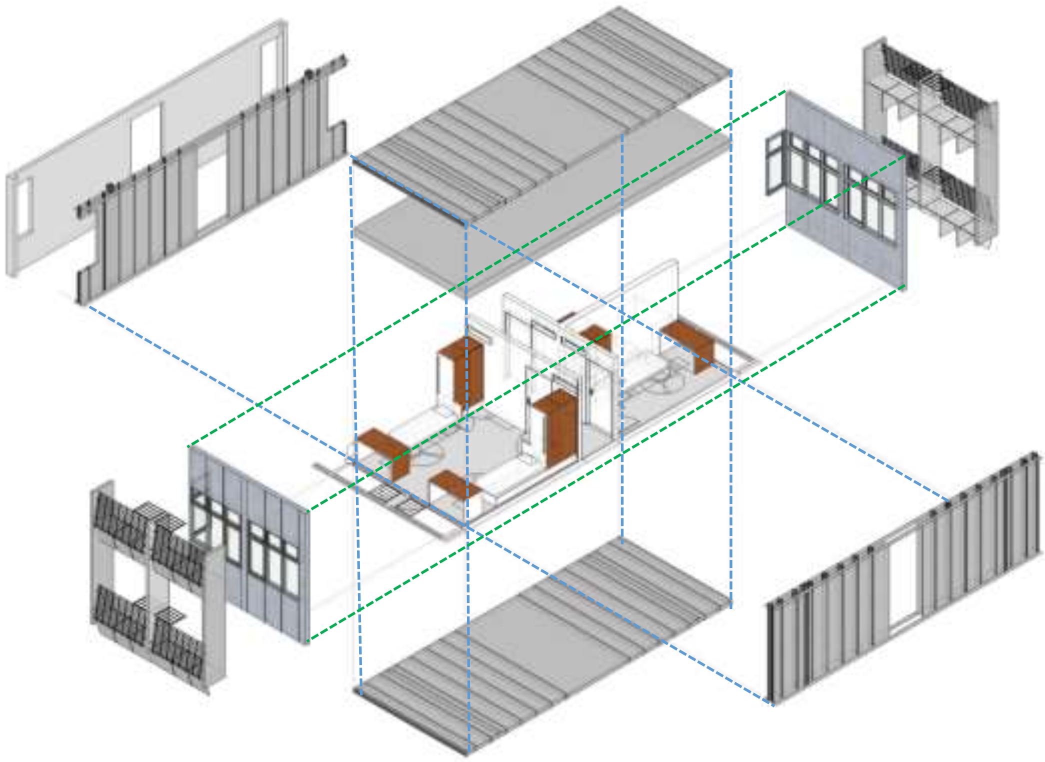
Building and Construction Authority

BIM for DfMA (Design for Manufacturing and Assembly) Essential Guide



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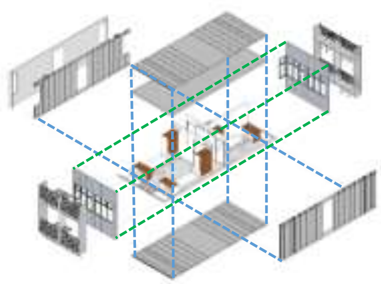

Cover image courtesy of P&T Consultants Pte Ltd

CONTENTS

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1 INTRODUCTION

1.1 BIM for DfMA: Building the Future

Around the world different industries, as diverse as automotive, aerospace, manufacturing and more, are innovating to improve their productivity. Through the application of new technology and automation, productivity in these industries is on the rise.

Construction companies in Singapore and internationally have also started to apply new design and productive technologies such as BIM and DfMA to their projects to realise significant productivity improvement as compared to the traditional methods that rely heavily on unskilled workforce and craft based methods.

To this end, this essential Guide intends to outline how DfMA projects can take advantage of BIM in the process. It covers the steps and considerations of BIM applications in a DfMA project.

Section 4 of this Guide (Case Studies) features some examples of local DfMA success stories. Some headline outcomes from these stories are as follows:

- At NTU North Hill Residence Hall, Mr. Andrew Tan, CEO of BBR Holdings (S) Ltd, expects up to a 40 per cent increase in labour productivity and 15 per cent reduction in construction timeframe for the project[1].
- The extension to the Crowne Plaza Changi Airport Hotel in Singapore has also adopted the DfMA approach which estimated a 50% reduction in the construction programme and 75% reduction in required manpower on site compared to traditional construction.

From these DfMA case studies, we realised that BIM has a role in making the project less risky by allowing the project team to simulate the construction virtually to identify potential pitfalls way before the actual construction begins.

With this guide and the case studies, we hope to see the BIM and DfMA work in harmony in the near future to change the way we build.

[1] *Source: The Business Times, BBR clinches $196m contract to build NTU student hostels, published 2 July 2014*

1.2 Changing the Way We Build

To bring the construction sector to a higher level of productivity and fundamentally change the way we design and construction, the Building and Construction Authority (BCA) encourages the industry to embrace the concept of Design for Manufacturing and Assembly (DfMA). To facilitate adoption of DfMA, BCA has put in place the Construction Productivity and Capability Fund (CPCF) to support firms that adopt productive technologies, develop the workforce and build capability.

As a result, increasing numbers of projects in Singapore are taking advantage of CPCF to pilot DfMA solutions. A number of developers have started to incorporate DfMA into their projects.

Currently, several ongoing building projects in Singapore which are successfully adopting Prefabricated Prefinished Volumetric Construction (PPVC) include:

- the NTU North Hill residence hall project;
- extension at Crowne Plaza Changi Airport Hotel;
- City Developments Limited's new Executive Condominium (EC) at Canberra Drive.

Since 2014, developers are required to use productive technologies such as PPVC and PBU for selected Government Land Sales (GLS) sites. The use of Prefabricated Bathroom Units (PBUs) was also mandated for all residential GLS sites to drive greater adoption of the technology. In addition, a minimum percentage of prefabrication level was set for Industrial Land Sale projects.

1.3 What is BIM for DfMA?

DfMA stands for Design for Manufacturing and Assembly. It stresses the importance of design for ease of manufacturing and assembling of components that will form the final product.

The DfMA approach when applied in the building and construction arena, requires a change in the relationship between design and construction. The design should focus on the methods by which the project is to be delivered, using off-site manufactured components where possible and planning for efficient logistics and assembly of these components on-site.

One way the DfMA approach can be managed effectively is through the use of Building Information Modelling (BIM). BIM is the process of producing a model of an asset that contains information about the asset. With BIM, the downstream DfMA activities (such as procurement, fabrication, transport, installation) through which projects are delivered on site will be more comprehensively linked to upstream activities (such as briefing, options appraisal and concept design). This will greatly enhance the common understanding of the project by all stakeholders.

Using BIM, digital models of the DfMA components and their connections can also be developed with an aim to streamline the processes of manufacturing and assembling these components. Over time, the knowledge gained from adopting a DfMA approach can be embedded in a set of structured data-rich models of standardized DfMA elements, such as PPVC, PBU, precast components or others for the industry to use. This will accelerate the adoption of the systematic approach to DfMA that BIM engenders.

1.4 Why adopt BIM for DfMA?

One of the main characteristics of DfMA is its component driven, modularisation and standardisation approach. DfMA also requires planning, adapting and optimising the design at the early stage to facilitate the fabrication of components or modules off-site and subsequently assembly on-site. Hence, the use of BIM as an object-driven tool and as an integrated collaborative environment provides potential benefits when leveraged on to drive the DfMA process.

Potential benefits of using BIM to optimise designs and the process for off-site manufacturing and on-site assembly in DfMA include:

1.5 Basic Concepts

1.5.1 Definition of Terms

Assembly

(1) Verb – the act of construction of a building through the combining and securing of manufactured components on site, generally in a planned, tested and carefully controlled sequence.
(2) Noun – an item formed by aggregating or combining different components or elements in part (Sub-Assembly) or in full (Assembly).

Asset

A finished building or other structure.

Component

Manufactured individual building element including prefabricated elements e.g. precast staircases, refuse chutes, structural members such as columns, reinforcement cages etc.

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.

Module

Similar to an assembly but typically self-contained, volumetric and room sized or enclosing usable space. Often standardized in form and/or volume.

Parts

Individual objects used in the construction of a building.

1.5.2 Examples of DfMA Elements

The list below outlines some examples of DfMA elements that are commonly used in construction projects. This is by no means a comprehensive list and elements should be developed for specific project needs.

Cross Laminated Timber (CLT)

Manufactured from wood harvested from sustainably managed forests and fabricated by binding layers of timber at 90 degrees with structural adhesives to produce a solid timber panel. Can be used as either structural or non-structural components in buildings.

Integrated Prefabricated M&E

Mechanical, electrical and distribution items prefabricated either as linear lengths, flat assemblies or integrated within volumetric modules.

Precast & Prefabricated Elements

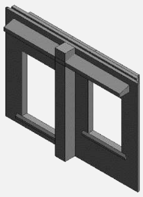
Elements that are manufactured in a controlled environment and are generally of better quality than in-situ elements e.g. staircases, facades, refuse chutes, parapets etc.

Prefabricated Bathroom Unit (PBU)

A bathroom unit fabricated and preassembled off-site complete with finishes, sanitary fittings, bathroom cabinets, concealed pipework, conduits and ceiling before delivering and installing in position on site.

Prefabricated Pre-Finished Volumetric Construction (PPVC)

Assembly of whole rooms, modules or apartment units complete with internal finishes and fixtures that are prefabricated off-site and installed on site to form modular apartments.

Components	**Integrated Components**	**Fully Integrated Components**	**Assets**
Structural (e.g. precast facade) 	PBU 	PPVC 	
Architectural (e.g. drywall) 	Integrated Precast Components 		
M&E (e.g. flexible sprinkler dropper) 	Integrated Prefab M&E 		

Examples of components, integrated and fully integrated components
(Image source: BCA)

2 GETTING STARTED

2.1 Process Overview

The DfMA approach, coupled with the use of BIM, can potentially make the industry become more integrated and productive at every stage of the project delivery – from design to construction and ultimately in operation.

2.1.1 Developing the DfMA Strategy

During the initial design stage, the DfMA strategy should be developed incorporating the use of BIM to facilitate the process. The strategy should respond to the following:

- Sector (e.g. housing, healthcare, infrastructure etc.)
- Availability of known products or suppliers;
- Likely degree of repeatability;
- Site/logical constraints;
- Project scale/value etc.

2.1.2 Step-by-Step Process

In the **early concept design** stage, DfMA elements can be identified and represented in the BIM model by 'placeholder' objects which are data rich but have limited geometry. These can be used to rapidly generate models to yield the estimated cost and procurement information etc. Scenarios and alternative options may be tested to optimise the project brief, assumptions and project drivers. These placeholders could also be used to identify the type of specialist to be involved to develop a DfMA solution.

As the **concept design** is developed, the building components could be advanced and refined in parallel. Early contractor involvement and supply chain engagement at this stage can help to validate the emerging concept designs in terms of the delivery of the project through DfMA and the adoption of standard solutions.

Throughout the **detailed design** stage, the models can be developed with increasing levels of sophistication in terms of geometry and data. As the components are better understood, further validation of the detailed design is possible versus the strategic brief with vastly improved levels of stakeholder certainty to aid the decision making process.

In the **pre-construction** phase, virtual building and prototyping exercises could be carried out using the digital models. The outcomes of the virtual prototyping can be used to carry out the real-world prototyping including training the operators, to refine the construction approach, test feasibility and maximise efficiency on site. This can take place in a safe, controlled environment and can be used to plan every aspect of manufacture, logistics and assembly long before the actual works start on site.

Real 3D models could also be produced from the digital models e.g. via 3D printing. Lessons learnt from prototyping can be incorporated back into the BIM model.

During the **construction** process, components can be tracked via serialization/QR coding or other means through each step of the manufacturing, packing, logistics and delivery process (see Section 3.5). The data that is inputted into the BIM model can also be used to manage marshalling of the components and the logistics of the site assembly process to minimise risk of delays.

Following **completion** of the project, the BIM model represents a data-rich digital version of the building that can be used for facility management. This could include tracking the scheduled maintenance of MEP items or necessary replacement of plant etc. The complete history and location of every component used in the construction can be recorded for future use and learning.

	Stages	Key BIM for DfMA Actions			
1	Project Brief Development	Build massing studies (e.g. orientation, area, volume etc.) based on site constraints and client and authorities' requirements	Capture rules for DfMA adoption (e.g. modular floor heights, grid dimensions etc.)	Develop DfMA & BIM implementation strategies and incorporate into BEP and project design	
2	Concept Design Development	Develop parametric "placeholder" objects for spaces with modular grids & layouts	Use space objects to generate multiple options to find 'best' fit to project brief	Generate room data sheets from space objects for approval of functional, environmental and finishes requirements	Use models to show concept for stakeholders' feedback and approvals
3	Detailed Design Development	Add in more details to space objects – geometry and data in detailed 3D models	Use objective analysis and reporting tools to demonstrate that brief objectives are achieved	Validate DfMA solutions through early contractor and supply chain engagement	Generate detailed part and whole models for different disciplines for early coordination
4	Pre-Construction	Refine models to incorporate inputs from DfMA supply chain	Develop overall construction programme schedule and sequencing	Develop fabrication & installation sequences, method statements, resource management plan etc.	Generate digital prototypes to verify construction strategy
5	Construction	Generate shop drawings for fabrication from models / Integrate fabrication with models	Track construction activities & resources based on planned programme and planned assembly sequence	Validate installation on-site and update models accordingly	
6	Post Completion	Ensure the as-built models are up-to-date for hand-over	Integrate as-built models with FM system		

Key BIM actions for the DfMA approach at the various stages
(Image source: BCA)

2.2 Project Strategy

2.2.1 Project Considerations

There are a number of considerations that should be made at the very earliest stage of the project that will help optimise BIM and DfMA integration in the project. These should be included as part of the development of a project Digital Delivery or BIM strategy.

1. Define Project BIM Strategy

It is important to develop a Digital Delivery or BIM strategy for the project that specifies the level of resolution and the types of data that need to be built into the BIM model at each design stage. This should be developed in accordance with the project brief and to achieve specific client objectives e.g. costing, sales and marketing, programming of site works.

2. Understand Whole Life Function of the BIM Model

Data sets that are inputted into a parametric BIM model can be used over the whole life span of the building, for more effective and efficient facility operation and management. It is therefore important to ensure that the data sets used are relevant to the facility management and operation teams and that they are applied in order to develop an understanding of the use of the asset and generate accurate as built information.

3. Agree on BIM Execution Plan

The BIM Execution Plan will outline the structure of the BIM modelling activities on the project. It will provide details of the relationships between the various parties involved in the project and the BIM model, the software platform that will be used, and the outputs that will be generated at each stage. The software platforms that are to be used on the project will depend on a number of factors and should be part of the BIM strategy. Different software platforms may also be used to perform different tasks as well as enable sharing and coordination of models as part of the Digital Delivery Strategy of the project. A template BIM execution plan has been prepared by BCA and is available at https://www.corenet.gov.sg/media/586149/Essential-Guide-BEP.pdf.

4. Early Involvement of Construction Specialists

To fully realise the potential for construction efficiencies through DfMA, it is important to have specialist construction knowledge as part of the design team from the early stages. This may be part of the services of the main design consultant on the project or it could be provided by a separate construction consultant.

Alternatively, early involvement of the Contractor and Specialist Subcontractors would enable the design team to tap on their experience and expertise in developing proposals for off-site fabrication and on-site assembly. This early input can also help in ensuring the cost-effectiveness of proposals, e.g. through identifying efficient mould sizes and shapes for precast elements or advising on material selection for finishes.

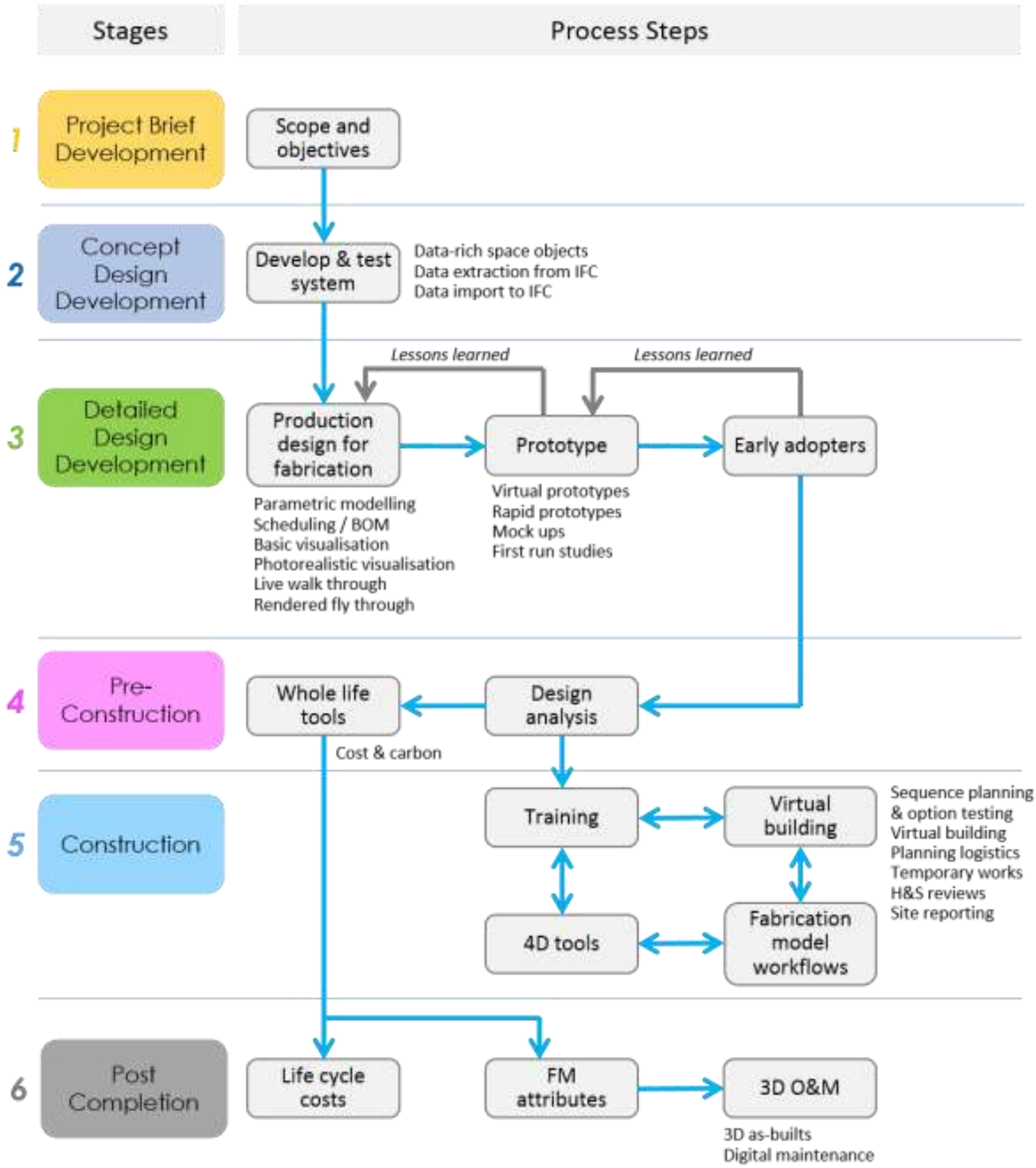
2.2.2 Process Shifts Through BIM

As BIM and DfMA practices become more sophisticated, the design process will start to generate substantial quantities of usable data and construction knowledge and inputs will be incorporated into the models at an earlier stage. The workflow below shows the potential for a shift in the way that construction projects are designed and procured.

BIM facilitates lessons learned to be rapidly incorporated between projects. Instead of individual projects acting as "standalone" or bespoke projects with minimal relationship with subsequent projects, the BIM model can act as a test-bed for a first, product based "system" comprising traditional construction elements and parametric prefabricated components, assembled in an efficient way.

The system design is developed through prototyping and realised on site in the first projects, with analysis and lessons learned at each phase.

The parametric components in the BIM model can be used to generate outputs to inform the construction process including training and virtual building simulations (see Section 3.5). The BIM model is also used to manage operations over the life cycle of the asset including life cycle costs. The system becomes more efficient, more effective and more intuitive with multiple deployments over a framework of projects rather than one standalone project.



Process shifts through BIM
(Image source: Bryden Wood)

2.3 BIM Outcomes & Model Progression

2.3.1 BIM Outcomes

A key aspect of planning the BIM process for a project is understanding the desired BIM outcomes that are planned for each stage of work and the benefits that are expected to be achieved. This should be based on the client's own goals and business requirements and may be weighted in order of importance. Defining the desired BIM outcomes early on will enable identification of requirements for data extraction from the BIM model. Defining incorporation of DfMA approaches as a desired BIM outcome will facilitate the adoption of these at the relevant project stage.

2.3.2 Data Extraction

At pre-determined intervals over the project lifecycle, data will need to be extracted from the BIM model. This data can be used for signing off by clients to ensure that the model development is appropriate for each stage, while providing valuable information about the design. The data can help make more informed decisions about different DfMA construction solutions.

Extracted data can be used for different purposes depending on the defined attributes for each stage. As more data attributes are added to the model the level of detail increases. The required attributes are based on the desired BIM outcomes and are decided by the client in collaboration with the author of the project BIM strategy at the start of the project.

An example of a possible structure for data extraction and usage is as follows. This is intended to show the underlying data which changes and grows over the course of the development of the BIM model. The model geometry may not differ substantially between stages - the difference lies in the extent and accuracy of the embedded data.

Stage 1: Project Brief Development

The BIM strategy for the project is established. Desired BIM outcomes are identified and data extraction requirements for subsequent stages are agreed on.

Stage 2: Concept Design Development

Intended to ensure that the design and specification are consistent with the client brief in terms of function, cost and sustainability. The model can show information such as massing (overall volume), space allocation (e.g. room sizes) and site location (e.g. northings and eastings).

Stage 3: Detailed Design Development

Intended to enable identification of contractors, procurement routes and supply chain. Accurate data will be included and visually represented. The model will represent the technical solution.

Stage 4: Pre-Construction

Intended to confirm that the developed design fully conforms to the client brief and to allow calculation and approval of the project agreed maximum price. The model is highly accurate, incorporates information from the supply chain and can be used for prototyping, first run studies and planning construction activities.

Stage 5: Construction

Intended to enable construction to take place in line with the project brief requirements. The model incorporates all amendments and lessons learned resulting from previous stages. The model is extremely accurate and can be used for construction.

Stage 6: Post Completion

Intended to represent the as-built asset including all installed systems, along with operational data sets to show how the asset is used. The model represents the building in use, including feedback information from Building Management Systems and facility management. The model is up-to-date and accurate at handover and will continue evolving over time to reflect the status of the building systems.

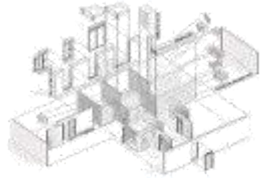
2.3.3 BIM Design Object Libraries

There are various sources for pre-designed BIM objects that already contain data attributes (although these may or may not be populated, and data sets may need to be altered to meet project specific requirements). Some manufacturers can provide BIM objects for their products either through their website or on request. These pre-modelled elements can provide further efficiencies to the process.

BIM objects to form facade of PPVC module

(Image source: P&T Consultants)

GETTING STARTED - BIM Outcomes & Model Progression

	Stages	Data/Model Development	
1	Project Brief Development	Spatial definition of modules. Establishment of volumes. Define basic parameters: room names, numbers, key dimensions, areas, volumes.	
2	Concept Design Development	Overall modules or assemblies with approximate quantities, size, shape, location and orientation. Basic architectural elements included. DfMA elements identified	
3	Detailed Design Development	Increased detail level with definition and modelling of all architectural, structural and MEP elements including DfMA components. Accurate specification, size, shape, function and location.	
4	Pre-Construction	Fully coordinated model with all disciplines integrated. Includes supply chain input. All components modelled and parameters populated for scheduling. Model is suitable for fabrication and assembly.	
5	Construction	Model is updated to reflect construction process (e.g. fabrication and install date) and design changes/modifications made on site. Model is fully coordinated and disciplines are integrated and current.	
6	Post Completion	Model is issued for facility operation and maintenance in "as built" and accurate state. Model is updated to reflect changes to the building over time.	

Model development and data required at the various stages
(Image source: Bryden Wood)

3 PROCESS

3.1 Stage 1: Project Brief Development

A successful design incorporating BIM and DfMA to best advantage starts with an accurate briefing process. On projects where the brief is not recorded formally, thoroughly and precisely, designs tend to veer away from the client's actual requirements. A clear brief allows the design to be checked continuously as it evolves. It also allows users and other stakeholders to make their own individual contributions to the design and specification of their own working environments.

1. Briefing Execution Plan

The structure and hierarchy of the client requirements should be established during a series of early workshops. Based on this a Briefing Execution Plan can be developed. The purpose of the Plan is to establish what aspect of the client's requirements need to be articulated at each stage for the design to progress smoothly. To deliver a quality solution, it is essential to identify as early as possible the details (technical, organisational, etc.) that will have a big impact on the design. The Plan also records who the stakeholders are, what information they should provide at each stage and what information they will need to approve.

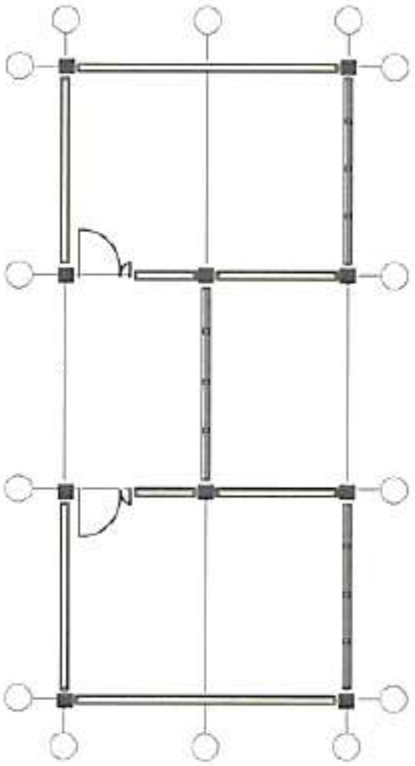
2. Brief Compliance Plan

Along with the Briefing Execution Plan, a Brief Compliance Plan can be developed to allow the client to assess whether the original brief is being met. This forms the basis of the project design management process, the aim being to eliminate unwanted design changes and cost overruns by "getting it right first time". One element of this Plan may be the establishment of assessment criteria for each design stage to confirm the degree of brief compliance of emerging proposals and allow sign off to proceed to the next stage.

The Plan may also include objective milestones (e.g. design cannot proceed unless compliance is at 90%).

3. Initial Design Considerations

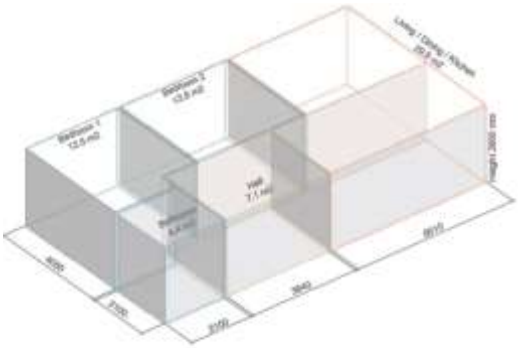
At the commencement of the design stage, attention should be given to aspects that will improve the efficiency of the design and facilitate the adoption of DfMA solutions. These aspects may include the adoption of standard grids driven by modular systems; standardisation of building elements and details (to enable modular prefabrication and provide economy of scale in procurement) and the adoption of a consistent range of floor to ceiling or slab to slab heights.



Defining a modular grid to enable repetition and standardisation
(Image source: BCA Buildability Series: Modular Coordination)

4. Early Spatial Models

Early spatial models can be developed in BIM to demonstrate compliance with the brief. These spatial models may only be basic space objects, however the objects should already be parametric, representing brief requirements for individual spaces (e.g. dimensions, light levels, finishes, fixtures, air changes/hr etc.) and the overall project (e.g. grid dimensions, planning requirements etc.). Early incorporation of brief requirements in a spatial model allows strategic decisions to be made at an early stage regarding the suitability of various available DfMA solutions. At this point, spatial models can be used to rapidly test multiple design scenarios and apply DfMA approaches to each one without requiring substantial design team effort.



Example of a spatial model to represent individual spaces
(Image source: Bryden Wood)

5. Analysis of the BIM Model

Data rich design objects that have been embedded in the BIM model can be filtered by attribute and outputs generated to show the level of compliance of the design with the key questions in the Brief Compliance Plan. Outputs can take the form of Excel schedules (e.g. accommodation schedule) as well as 2D and 3D viewing models. This will allow the project to be assessed by the client without needing to access the BIM model. Analysis of the filtered model can also help to identify inefficiencies and optimise the design at an early stage, e.g. by reducing circulation areas.

3.2 Stage 2: Concept Design Development

	Stages	Key BIM for DfMA Actions			
2	Concept Design Development	Develop parametric "placeholder" objects for spaces with modular grids & layouts	Use space objects to generate multiple options to find 'best' fit to project brief	Generate room data sheets from space objects for approval of functional, environmental and finishes requirements	Use models to show concept for stakeholders' feedback and approvals

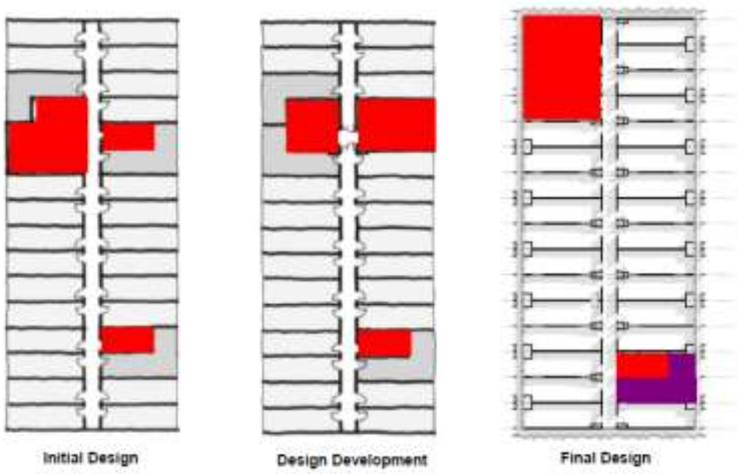
During the development of the design, the level of detail of the spatial model is developed and refined to reflect design decisions made as the project develops. While the model is still comparatively simple and easily manipulated, multiple scenarios can be tested to find the "best fit" solution to the project brief. The models should also still be flexible enough to accommodate changing client requirements. The model can be used to test the feasibility and comparative benefits of integrating different DfMA approaches into the project.

It is during this stage that the degree of DfMA adoption on the project should be defined, and to what extent supply chain integration is required to develop the DfMA solution, as part of the project DfMA strategy. This may be done in conjunction with the construction approach for individual components.

3.2.1 Initial Design Modelling

Commencing the initial design in BIM can make the job of developing a DfMA strategy for a project easier. The use of 3D modelling can also help with spatial visualisation as the design develops.

The use of rapid 3D modelling tools may be of benefit when modelling possible scenarios or solutions to a design problem. However, many rapidly generated 3D models are not as intelligent or interoperable with other platforms and so any outputs may have to be duplicated in BIM to be used on the project.



Design development of PPVC modules at different stages

(Image source: Dragages Singapore)

3.2.2 Degree of DfMA Adoption

The DfMA approach offers a wide spectrum of solutions and selection of the preferred degree of DfMA adoption should be in response to project specific drivers including sector, supply chain capability, likely degree of repeatability, site/ logistics constraints, etc. The higher the level of DfMA adoption, the greater the standardisation efficiencies that are possible.

At lower levels of DfMA adoption, a project might be delivered traditionally but with consideration given to the logistics and management of the construction process to adopt a “site assembly” type of approach where labour operates more efficiently and in teams. Standardisation in design may be considered to an extent. It is also possible to incorporate some DfMA elements in a project that is primarily traditionally delivered, e.g. prefabricated plant elements, prefabricated doorsets or windows, etc.

At higher levels of DfMA adoption, the design will be highly standardised and a significant proportion of the project will be delivered using off-site fabricated components (e.g. PPVC, PBU, precast stairs and household shelters etc.). These off-site fabricated components will be modelled using BIM and can be efficiently assembled on site.

At the highest level of DfMA adoption, all or nearly all of the project is designed and delivered using prefabricated construction components with as high a degree of standardisation in fabrication as possible, procured from the supply chain in large quantities and efficiently assembled on site.

3.2.3 Supply Chain Integration

The BIM platform should allow technologies and solutions currently offered by the supply chain to be integrated into the project. Many supply chain partners provide BIM models of their solutions in the native file formats or other BIM platforms. These models can be incorporated directly into the BIM library of components for the project. In some cases, some reworks may be required to render third party models compatible with the project models.

A specification should be produced by the project design team or BIM coordinator for the format in which supply chain partners should issue the model information (including BIM standards, naming conventions, standard attributes etc.).

The selection of DfMA solutions should be carried out through a comprehensive review of solutions that are currently available from the market and have proven cost information, carbon content, lead time, operation and maintenance data, and a capable supply chain already in place.

3.2.4 Defining Component Libraries

The potential for standardization of construction components depends on various factors such as the project requirements and the BIM capability of the project team As construction components are standardized, the project can achieve lower costs and carbon through economies of scale in procurement and improved construction efficiency. To achieve this, it is necessary to develop a library of components during the design phase that will be used on the project.

The 10:80:10 principle

For many clients with a framework of projects, the '10:80:10' principle states that for any project:

- 10% relates to anomalies (site layout, ground conditions etc.);
- 80% of the project (this may be measured in terms of cost, area, element types etc.) can be standardised in some way;
- 10% relates to enhancements over and above the standard specifications.

In some cases, the degree of standardisation possible may in fact be even higher than 80%.

It is important for any construction approach to respond to site and project specific requirements since solutions that are not site and project specific will introduce waste (e.g. through over providing accommodation). It is therefore critical to achieve the appropriate level of mass customisation where standardised solutions are adopted to achieve site and project specific requirements.

The first step to achieving this is to define and build component libraries for the elements of the building for which standardisation will be appropriate. The objectives will be to:

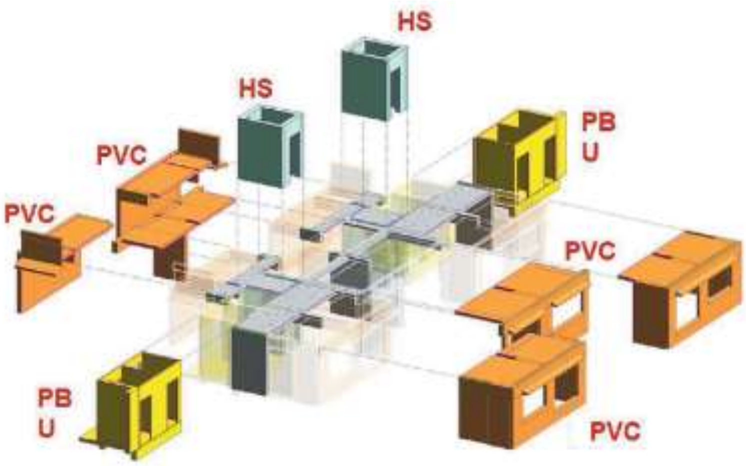
- Ascertain the library of components that would be required to describe e.g. 80% of the asset (in terms of physical content /design standards);
- Develop a selection of key elements as a first study to demonstrate the outputs.

Determining a prefabrication approach based on a standardized building layout
(Image source: P&T Consultants)

The steps involved could be:

- Carry out a design review to identify standardisation opportunities;
- Use the outputs from the design review to create a list of possible components;
- Rank these by the value that a standardised BIM component would bring (e.g. application to other projects, extent of information captured, potential cost or programme savings etc.);
- Pick a number of highly ranked components and review existing brief information for them from 'first principles'. Test these against project standards;
- Develop optimised briefs for each component;
- Undertake stakeholder engagement to agree on the likely attributes that the client would like to track;
- Build parametric BIM models for each component;
- Test these models for robustness and operability;
- Test a number of case studies on real projects;
- Create a programme for the preparation of the remainder of the component library to describe much of the asset as possible or desired.

The series of sample elements that would be developed through the above process could be used to communicate the design intention of the standardisation approach to the project stakeholders and facilitate buy-in to the adoption of these on the project.



Exploded axonometric image of an apartment layout showing the integration of prefabricated bathroom units (PBU), prefabricated volumetric units (PVC) and precast household shelters (HS)

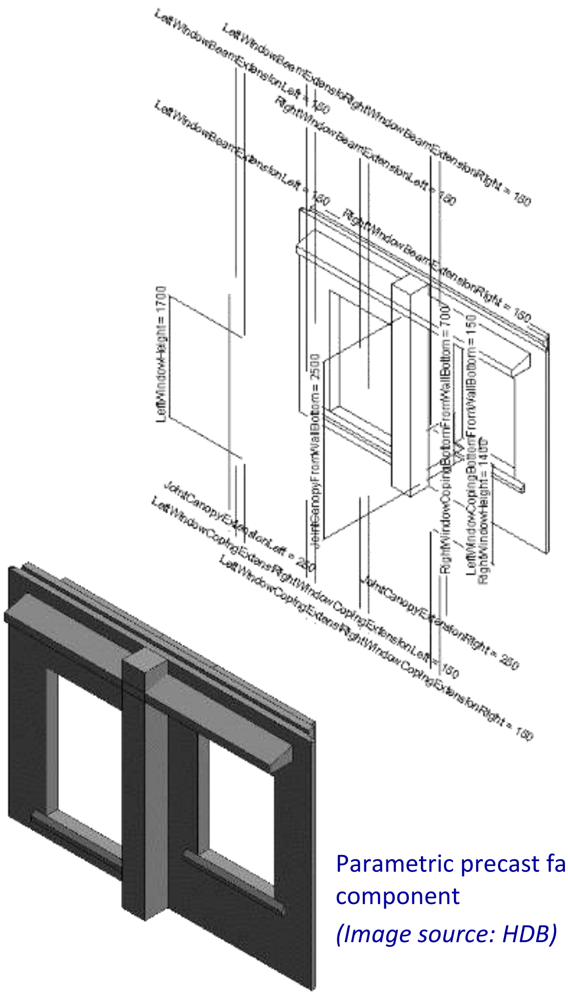
(Image source: P&T Consultants)

3.2.5 Parametric Components

The creation of a library of standard parametric components in BIM will enable consultants to efficiently deploy those components into models to build assemblies, modules and whole buildings with greater certainty from an early stage. Examples of parametric components include structural members, fixtures and fittings, precast components, modular plant (mechanical, electrical, public health or otherwise), etc. Component libraries can be established as a "plug and play" catalogue of design elements that can be configured in a set variety of ways to form buildings. Some examples of this technique being deployed in the manufacturing sector are Ikea, where a limited number of flat packed components can be efficiently transported and assembled at home, and Lego, where a limited range of basic blocks can be configured in limitless ways.

When standard components are parametric or data-rich, the data they contain can quickly be extracted from the BIM model and tabulated or scheduled. International standards for data sets do exist (e.g. COBie (Construction Operations Building Information Exchange)). However, clients can adjust and add to these to form requirements for data outputs from BIM modelling. Some data attributes that may be incorporated into parametric components include dimensions, material, supplier, cost, lead time, structural criteria, performance criteria and MEP criteria such as designed flow rate or cooling load. Rapid scheduling and analysis of parametric data from standard components allows the design to be efficiently configured to suit the project needs without compromising on the design intent.

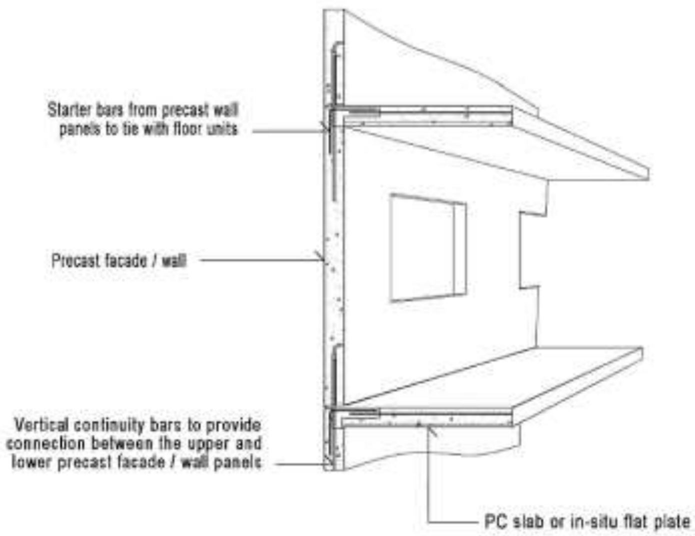
The identification and development of standard parametric components should be established at the early design stage and the detail of each component developed as the design progressed. Basic "placeholder" components containing only the dimensional information can be used for space planning and gradually become more visually and data rich over the design process. Through the structure of BIM software which separates element creation from project model files, this exercise of refining component detail can take place concurrently with the evolution of the main building design. Component families that are critical to the overall design, e.g. operating theatres in hospitals, may be fast tracked in terms of data attribution to ensure compliance with the brief at an earlier stage.



Parametric precast facade component
(Image source: HDB)

Some general rules of thumb for the establishment of parametric components in BIM include the following:

- Standardise sizes and shapes of components in alignment with supply chain capability to ensure they can be mass produced with competitive pricing and economy of scale and transported in line with logistical requirements e.g. vehicle size;
- Ensure that the weight and overall dimensions of components is such that hoisting and installation in place will be achievable in an efficient manner;
- Ensure that assigned parameters are aligned with client and project requirements and that data is embedded at the appropriate stage;
- Create modular components that allow for reuse and repeatability;
- Incorporate data to enable more efficient downstream activities e.g. costing, scheduling, fabrication and facility management, and ensure adequate tools are in place for utilising this data at the appropriate stage;
- Take into consideration assembly issues in the design of components, e.g. hoisting strategy, production and erection tolerances, lifting strategy etc.
- Develop robust and standardised connection details between adjoining components and between components and conventional construction elements, with specialist construction input if required. Watertightness and workmanship should also be considered.



Design of a connection detail between precast wall and floor slabs
(Image source: BCA Buildable Series – Buildable Solutions for High-Rise Residential Development)

3.3 Stage 3: Detailed Design Development

	Stages	Key BIM for DfMA Actions			
3	Detailed Design Development	Add in more details to space objects – geometry and data in detailed 3D models	Use objective analysis and reporting tools to demonstrate that brief objectives are achieved	Validate DfMA solutions through early contractor and supply chain engagement	Generate detailed part and whole models for different disciplines for early coordination

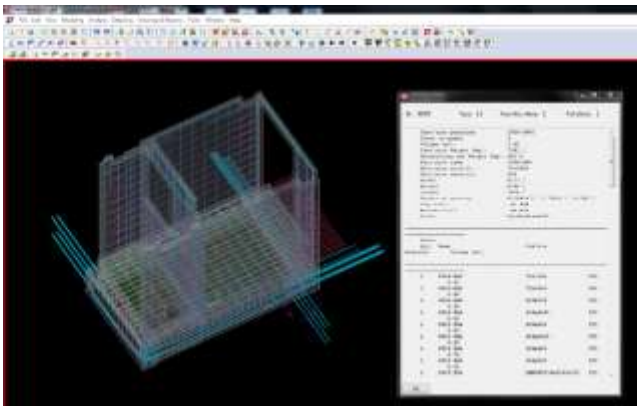
3.3.1 Building Component Details

During the detailed design phase, the project design is developed for construction. The component libraries are enhanced with additional levels of data and represented with detailed 3D models to enable fabrication. Whole building BIM models are developed to enable coordination and clash detection between structures, MEP and architectural elements. As the detail of the individual component is developed, it is important to retain the focus on standardisation to ensure economies of scale are preserved. As the design evolves, parametric workflows in the BIM model can help manage and automate project changes (e.g. overall unit sizes or apartment mix in residential developments) to improve the efficiency of design development.

In the earlier project stages, basic quantities may be extracted from the BIM model. However, as components become more detailed in the level of graphical realisation and data attribution, the ability to accurately extract quantities from the BIM model is increased.

Quantities scheduled from BIM models can be used for more accurate cost estimation and management during the development of detailed designs. This can allow cost impacts to be considered during the design process to allow value opportunities to be captured early. Greater cost certainty is also possible earlier as the level of data attribution increases, thus improving the level of confidence in the cost estimate at the point when initial funding needs to be released.

Data extracted from the BIM model can also be used for supply chain and procurement activities (to ensure a viable and competitive supply chain exists for all materials) leading up to construction, and inventory management during the construction process. Integration of cost and inventory management processes can help reduce the amount of material wasted during the construction process, reducing the amount of carbon emissions embodied in the project, and reducing the direct cost of transporting waste to landfill.



Quantity Take-off of rebars in a PVC module
(Image source: Teambuild/ Integrated Precast Solutions)

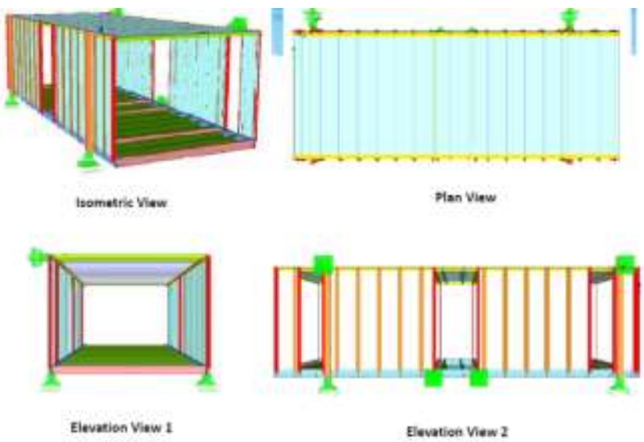
3.3.2 Other Considerations

The detailed design stage is the final stage of design development before procurement activities commence. Client sign off should be received prior to the commencement of pre-construction activities to confirm that the brief objectives have been achieved. A range of considerations should be made during the detailed design phase to ensure the suitability of the DfMA approach that has been proposed. These include:

1. Structural Considerations

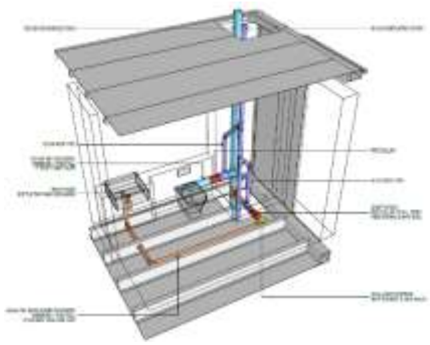
The weight of prefabricated components and modules should be considered in the structural design and analysis of the project. Other factors such as the structural strength of the receiving platform and the design of the hoisting and lifting devices to facilitate the installation will also need to be considered during the design stage prior to manufacturing.

3D virtual BIM models of the components and modules could be used to aid the design and analysis process and incorporate any specific requirements for subsequent fabrication and assembly. Structural analysis of the model should be performed not only on the finished asset but also during the intermediate stages of assembly to facilitate the identification and design of any required temporary supports or propping.



2. MEP Considerations

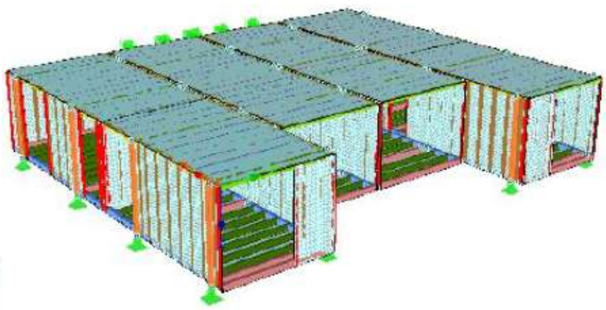
Creating 3D BIM models of the assemblies or modules will help consultants in determining the placement and routing of the MEP services within the modules and for modules interfacing with other components, modules or traditionally constructed elements of the works.



Integrating MEP services within a PPVC module
(Image Source: P&T Consultants)

Accessibility to MEP shafts or ducts within the modules for subsequent connection and maintenance should be catered for in the design of the modules and floor layout. The fabrication sequence and integration with the architectural and structural works within the module is also critical to the fabrication process.

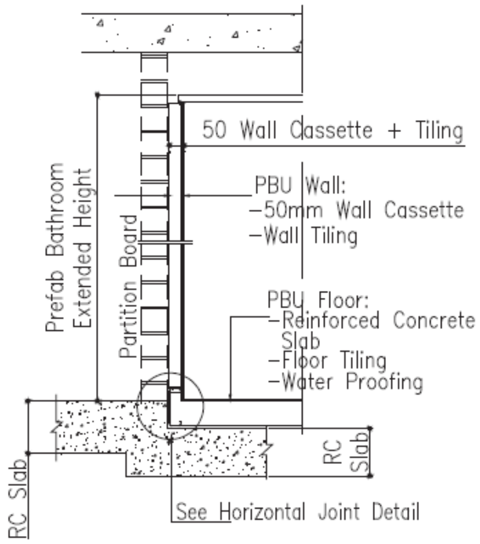
Coordination and clash detection can be carried out effectively with BIM and is essential to ensure that services embedded or concealed in the components and modules can be provided for during fabrication and correctly aligned for subsequent assembly on site.



Performing RFEM Analysis on a PPVC module
(Image Source: Singapore Piling & Civil Engineering (Structural Design by Ronnie & Koh))

3. Connection and Joint Details

DfMA component connection details should be designed to meet structural requirements and design and performance criteria such as strength, ductility, fire resistance and stability. They should also satisfy any requirements for the safe manufacture, transport and erection of the component, assembly or module. Joint and connection details should be standardised as far as possible but still allow for production and installation tolerances.



Connection detail between PBU and concrete floor
(Image source: BCA Buildability Series – What you need to know about Prefabricated Bathroom Unit (PBU))

4. Supply Chain Validation

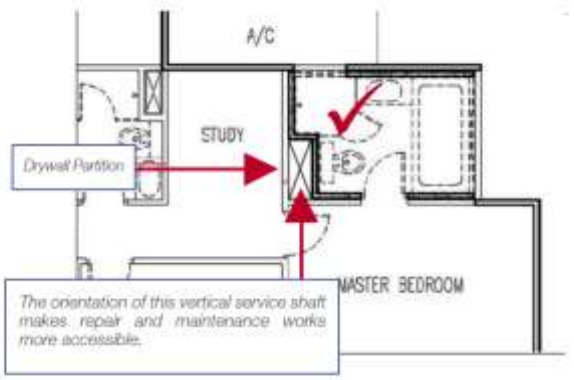
The DfMA solutions that have been developed should be validated with the supply chain to test procurement and timescale assumptions and ensure the feasibility of the project proposals prior to commencement of the fabrication works. This can be carried out through direct contact with the supply chain, potentially in partnership with the contractor through early engagement.

5. Accessibility for Assembly and Maintenance

Prefabricated components should be designed in such a way as to ensure the feasibility of assembly. Maintaining access to make physical connections between components is essential. Using the BIM model to test the assembly strategy is a useful way to ensure this.

Design layouts should ensure that the location of services, vertical stacks and maintenance panels within the modules or units are accessible for future maintenance, renovation and replacement.

For example, access panels could be provided in the ceiling of a PBU to provide access for repair and replacement of overhead services. The BIM model can be used to simulate and plan replacement activities to ensure access is feasible.



Designing with access for maintenance works in mind
(Image source: BCA CONQUAS Enhancement Series – Good Industry Practices - Prefabricated Bathroom Unit (PBU))

3.3.3 Sustainability

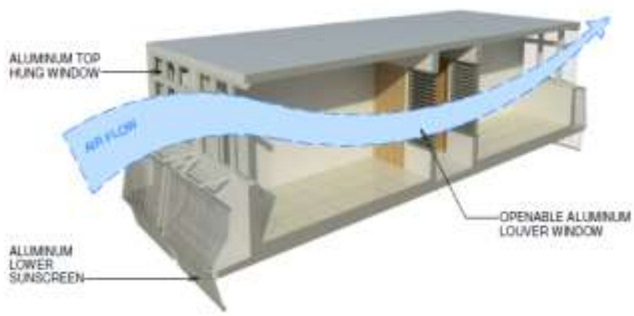
The design process should seek to consider the whole life cycle of fabrication and construction, not just the operational use. In order to do this effectively it is necessary to understand the facility in question, its build sequence, materials used, operational energy/carbon emissions and what factors can be influenced in the design to affect the outcomes in terms of carbon performance.

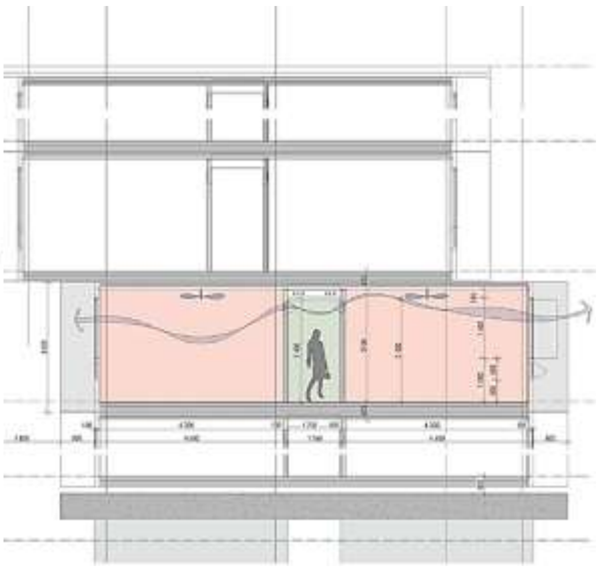
The use of data rich 3D BIM modelling significantly simplifies this analysis – for example BIM modelling enables quantities of materials to be rapidly estimated and their embodied carbon calculated. Energy databases such as the Bath University 'Inventory of Carbon and Energy' allow buildings, or elements of buildings to be analysed. This information can be used to help drive decisions on materials, and construction methods. By facilitating analysis of design iterations BIM can help the project team identify the best performing option from a sustainability viewpoint.

The use of DfMA components and approaches on building projects can dramatically reduce the embodied carbon in the finished project. For example, the Buildoffsite group in the UK estimates that through the use of DfMA, traffic movements to and from construction sites can be reduced by up to 20% and site overheads (welfare, lighting etc.) can be reduced by up to 50%. Additionally, according to Buildoffsite, improved performance of environmental control systems in DfMA projects (due to the high standard of assembly and commissioning) can result in up to 30% reduction in carbon in use compared to a traditionally built project.

Projects using DfMA elements can also generate substantially less waste than conventionally delivered projects as components are manufactured in factories where waste can be reused. Standardised dimensions can also help by reducing waste generated by offcuts.

Adopting assembly techniques on construction sites using prefabricated components can also remove the need for wet trades on site which reduces the overall water consumption of the project.





Using BIM to study the 3D spatial space in green sustainable living environment by ensuring adequate wind flow velocity across each unit – a prerequisite requirement for Green Mark Platinum *(Image Source: P&T Consultants)*

A wide range of design tools are available to allow the comparative carbon performance of different systems and approaches (including DfMA solutions) to be analysed throughout the design process. Examples of such tools include:

- Simple carbon calculation spread sheets for early stage rapid assessment of operational carbon emissions allowing the impact of design choices to be estimated as the design progresses.

- Dynamic thermal modelling, using specialist software for more in depth analysis of operational energy and carbon emissions. These models would normally be evolved throughout the design and construction period and be used to predict operational energy and carbon emissions and confirm compliance with building regulations and planning conditions. Since these models are usually developed in standalone software (separate from the BIM model) the process of information transfer should be considered to minimise any impact on design team efficiency.

- Life cycle analysis (LCA) tools. Life cycle analysis can be a powerful tool in influencing the design solution. Typical systems to which LCA could be applied would include: ventilation plant, cooling systems and façade refurbishment. LCA outcomes can have a significant result on the performance of the finalised design of a building. The possible savings in operational energy and carbon emissions can far outweigh the additional capital costs required to provide an optimised alternative design solution.

- Use of BIM modelling to estimate embodied carbon in DfMA components (e.g. materials, factory labour and operational emissions, transportation logistics) and embodied carbon in site assembly (e.g. labour, craneage, site overheads) and to enable comparative analysis between alternative systems.

3.4 Stage 4: Pre-Construction

	Stages	Key BIM for DfMA Actions			
4	Pre-Construction	Refine models to incorporate inputs from DfMA supply chain	Develop overall construction programme schedule and sequencing	Develop fabrication & installation sequences, method statements, resource management plan etc.	Generate digital prototypes to verify construction strategy

3.4.1 Detailing for Fabrication

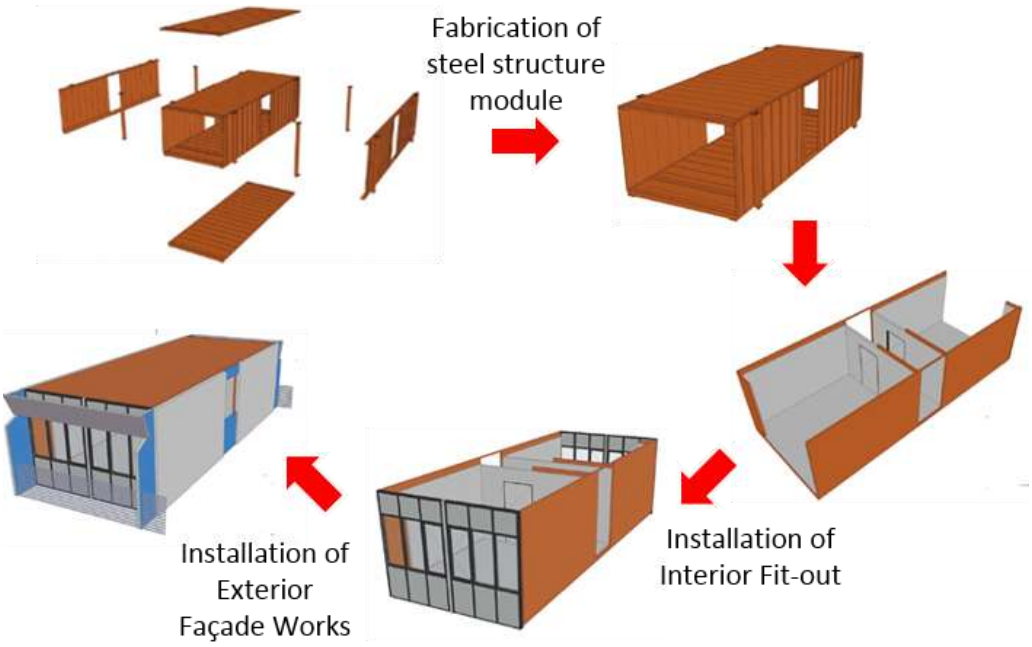
The capability of the fabricator will determine the way in which the model is developed to a level that will allow fabrication of the components. Some fabricators have the capability to input BIM models directly into CNC machines (see Section 3.6) for fabrication. Others have the capability to inspect and extract information directly from BIM models, and others will rely on extracted 2D outputs (e.g. drawings and schedules).

At the pre-construction stage the BIM model can be checked, analysed and interrogated to ensure that the design is fully coordinated and clash free with all attributes populated, the construction and assembly approach is feasible and efficient, and the requirements of each design discipline have been incorporated. In many cases fabricators can also share their standard components, connection and assembly details with the design consultants in the form of parametric BIM models or other outputs to allow for integration into the project models.

This information should be requested from fabricators as it will help ensure coordination and integration across the project which will improve the overall efficiency of project delivery.

Incorporating this high degree of integration of fabrication and assembly information into the project will provide a higher level of certainty around the constructability of the project. This high degree of certainty is possible through using the BIM model as a prototype for the real world project - first in the virtual space, and then through the generation of physical prototypes.

There will be a point in the project where component design needs to be released for fabrication. At this point the design will need to be frozen with no further changes. Some clients may require the ability to exert change on areas of the project until a late stage and the component design should be developed with this in mind, retaining future flexibility where required. When components have been frozen for fabrication this can be represented in the BIM model.



Sequencing the fabrication of a PPVC module using BIM
(Image source: P&T Consultants)

3.4.2 Prototyping

In the development of industrialised products using DfMA principles, the purpose of a prototype is to:

- test and trial the new design;
- test and optimise installation or construction sequences;
- identify opportunities to refine and improve the proposed design, installation etc. before commencing large scale manufacture.

The ultimate aim of prototyping is risk reduction, by learning as much as possible from the process in a controlled environment, off the project critical path, to inform the development of the 'production run' of the system or element.

There are varying degrees of 'prototype', which provide differing levels of feedback and learning but have commensurate levels of time and cost associated with them. These can be broadly categorised into two types: digital (virtual) prototypes produced using BIM, and physical (real world) prototypes. Physical (real world) prototypes include:

- rapid prototypes;
- mock ups;
- full scale prototypes;
- "first run" studies.

Not all projects require every level of prototyping, but it can be useful to carry out a number of steps prior to entering full production.

1. Digital (Virtual) Prototypes

Sophisticated software platforms can be used to simulate real life conditions and undertake analysis, using the BIM model as a platform, without the need to produce physical elements. In product design software, digital components can have 'real' properties to allow analysis including:

- mass and centre of gravity (e.g. craneage studies);
- failure modes and effects analysis (FMEA);
- computational fluid dynamics.

A virtual prototype of PPVC guest room with proposed finishes produced for client's review
(Image source: Dragages Singapore)

Components can be developed in the BIM model to a fabrication level of detail, allowing digital information to be sent direct to the supply chain for fabrication without supplier-provided design. For this to be feasible, the following aspects should be considered:

- Components should incorporate the material specification and manufacture/fabrication method;
- Interface connections should be developed with regard to structural performance, water/ moisture/vapour penetration, acoustics, assembly efficiency etc.;
- Lifting, handling and transportation strategies should be developed for each component and sub-assembly.

A step-by-step process could be:

- Develop a model of a sample section of the initial plot design concept.
- Develop the model to include construction sequence, program, supply chain and resulting costing modelling;
- Filter the model to determine quantities, program, site labour histograms etc.;
- Assess the outcomes of the 'Virtual Build' against local benchmark norms for cost and against aesthetic and quality issues;
- Consider modifications to the components on the component deployment and assembly techniques.

This will be used to deliver fabrication information on the components.

Depending on the scale of the project, literally millions of the same component may be required in many cases. One of the key drivers must be to maximise the potential for a manufactured solution to allow 'assembly' not 'construction'.

2. Rapid Prototypes

Rapid prototypes are a scale model (which may be smaller or in some cases larger than the final element) of a physical part or assembly which are developed using a 3D CAD model, with parts created using 3D printing technology. These can be used to test interfaces, tolerances etc.

3. Mock Ups

Mock ups comprise fabrication of a scale model of an assembly or element, but not necessarily in the final materials that will be used. For example, a mock up in timber and cardboard is relatively quick and easy to amend and adjust, while the final product may be proposed in steel or concrete. Mock ups allow a number of options to be tested very quickly, and refinements easily incorporated before expending the time and cost associated with a full prototype.

4. Full Scale Prototypes

This is a full or partial section of an element or assembly, usually at full scale and using the final proposed materials. A prototype can be used to test the physical characteristics of an element or system as well as installation methods. Prototypes are typically created for learning purposes only, not for deploying in a 'live' environment. Significant issues may be identified in the creation of a prototype.

5. First Run Studies

This is the first 'production run' version of an element, which is used to identify minor issues. It is anticipated that the 'first run' will, with minor modifications, be used in the final 'live' environment for which the element is proposed.

Mockup of a structural chassis for a PPVC module
(Image source: P&T Consultants)

Benefits of Prototyping

The benefits of prototyping include:

- better, more targeted engagement with suppliers as the required end product will be extremely well understood and defined;
- more objective assessment of suppliers as the quality of their products can be measured against the standard defined and achieved during prototyping;
- greater consistency across different plots of the same project - labour teams will be able to work on any plot as the methods of construction will be identical across the project. Suppliers' components will be able to be deployed on any plot;
- assembly teams can be trained using the prototype before going on site, so that productivity on site will be high from day 1 (no 'learning curve' on actual buildings);
- greater opportunity for measuring progress on site, creating feedback loops and driving continual improvement.

The benefits of creating prototypes are particularly high for large projects. Before embarking on a process of installing thousands of square metres of structure, a relatively small prototype could be used to:

- demonstrate systems in practice;
- optimise the assembly sequence and create installation/health & safety guides;
- provide detailed data regarding assembly to inform construction programmes, logistics planning etc. etc. with a relatively high degree of certainty (compared to standard practice which is necessarily based on assumptions);
- provide training for assembly crews, crane operators etc.

3.5 Stage 5: Construction

	Stages	Key BIM for DfMA Actions		
5	Construction	Generate shop drawings for fabrication from models / Integrate fabrication with models	Track construction activities & resources based on planned programme and planned assembly sequence	Validate installation on-site and update models accordingly

The construction stage of a DfMA project is split into two parts - fabrication away from the construction site (in a controlled factory environment) and assembly on the construction site. Both activities can take place more or less in parallel - enabling works on site to commence while the initial prefabricated units are being made in the factory. Factory fabrication can then continue throughout the erection process with deliveries from the factory to site either on a "just in time" basis or via a staging or marshalling facility. It is advisable to have some form of staging so that factory works can stay ahead of site works.

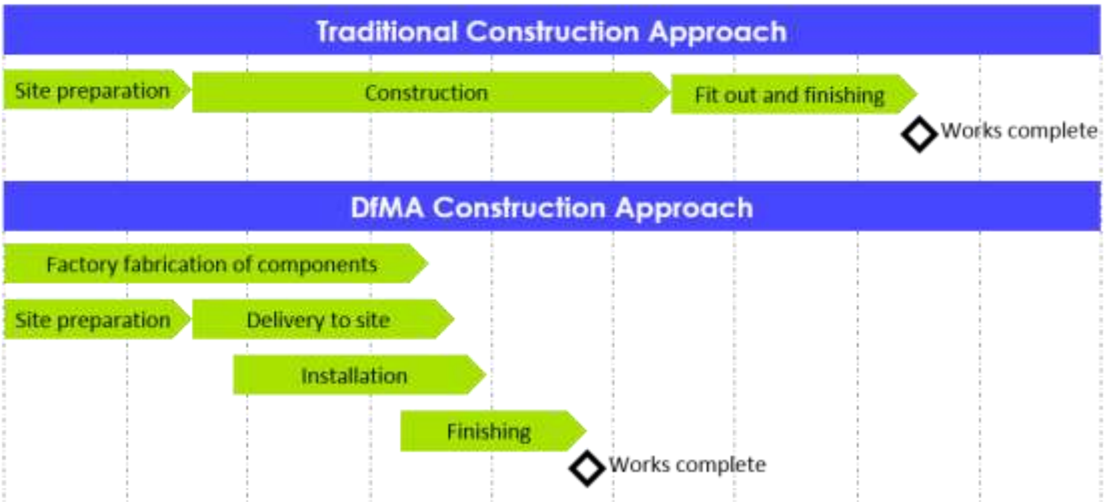
3.5.1 Fabrication

Fabrication of components and modules off-site in a controlled environment allows high standards of quality to be achieved with easier implementation of health and safety procedures. Fabrication can be directly linked to the BIM model with schedules of quantities easily extracted. Any changes made to the design of prefabricated elements can be directly communicated to the factory team. Feedback from the factory on fabrication techniques can be incorporated back into the model by the design team.

Factors such as the structural analysis of joints, lifting loads, assembly methods, connection designs and site constraints should be considered in the design prior to the fabrication of components, assemblies and modules. The optimal dimensions of prefabricated items depends largely on the capacity of the lifting cranes at the fabrication yard and site as well as the constraints of physical transportation.

Prefabricated parts can be planned, standardised and designed in detail using BIM and fabricated from exports from the BIM model. Fabricating directly from the model or from model exports can reduce manufacturing errors and reworks compared to fabrication from factory-produced shop drawings.

The BIM model can be used to develop a fabrication strategy to ensure that factory works are carried out in an efficient, assembly line manner with different fabrication tasks taking place in dedicated, sequentially ordered workstations in the factory. The sequence of applying finishes should be considered to avoid the need for rework. The BIM model can also be used for design and coordination of MEP systems within prefabricated elements.



Typical compressed project schedule for a DfMA construction approach – concurrent fabrication, delivery and installation activities on and off-site
(Image Source: Bryden Wood)

3.5.2 Delivery to Site

The optimal component size and transportation method should be considered especially for heavy (e.g. precast) or volumetric (e.g. PPVC) units. Transportation difficulties may limit the design, size and shape of heavy or volumetric units that can be delivered to site. Delivery routes can be determined and built into the site layout and logistics planning. Routes from fabrication facilities to site can be mapped digitally and tested during the development of the delivery plan. Aspects such as maintaining good traffic flow around the site and access for emergency vehicles during the planning of deliveries should be considered.

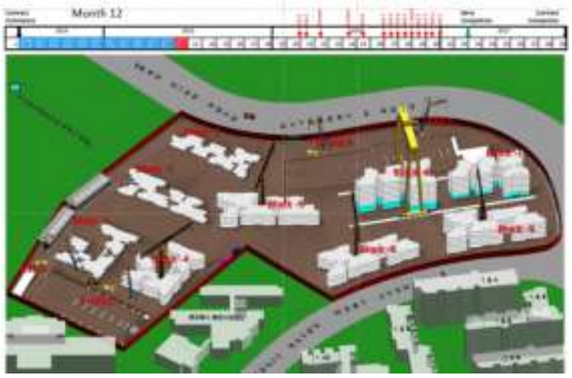
Where transportation is a significant aspect of the prefabrication strategy, ensuring that the size and weight of components are considered to ensure efficient transportation can help the overall delivery process. For example, prefabricated components that are being shipped internationally could be sized in accordance with standard shipping container dimensions to allow the maximum quantity of material to be transported in each container.

Delivery and hoisting of PPVC module on site
(Image Source: Singapore Piling & Civil Engineering)

3.5.2 Site Logistics

The positioning of required heavy construction equipment (e.g. mobile, tower or gantry cranes) must be considered and built into the site logistics plan, taking into account site access, erection capability and ground stability. Consideration must also be given to manoeuvring space and turning circles for over-sized vehicles and equipment within the vicinity of the construction site without interfering with the assembly works. The risk to overhead infrastructure and neighbouring properties during handling and lifting should be taken into account.

Site activities can be planned and coordinated efficiently using the BIM model, to optimise the utilisation of the construction equipment and resources deployed on site.



Planning the resources and construction sequence *(Image Source: Teambuild)*

3.5.3 Assembly

Throughout the DfMA design process, the project design should be optimised with efficiency of delivery, assembly and installation in mind. Prefabricated parts should be designed to minimise handling and simplify connections, resulting in a more efficient on-site assembly process.

The BIM model should be managed and kept up to date over the course of the construction phase to provide a record of the built works. The BIM model may be centrally held in the project office and printed outputs generated from it for use by site operators, or it could be accessed directly from the site by use of iPads or similar tablet hardware. This would ensure that site operators would always have access to the most up-to-date information.

The BIM model can also be used to visualise and plan the sequence of assembly works and the installation of each prefabricated component, assembly or module, including the development of digital method statements.

The weight of each prefabricated component should be taken into account when developing a lifting or hoisting plan. Capacity and utilisation planning for cranes and other lifting and hoisting equipment can also allow these expensive assets to be utilised optimally over the course of the construction period. During assembly BIM can be used as a tool to help organise the project, plan and control the flow of information and schedule and track the delivery of prefabricated parts and assembly of the asset.

To an extent, it is possible to incorporate estimated labour requirements for assembly and installation (e.g. number of personnel needed, estimated installation time etc.) into the BIM model. This information can be used for detailed resource and manpower planning to help ensure that an appropriate level of manpower is allocated and that labour on site is working as efficiently as possible. Resource plans can be developed to take into account the parallel activities of on-site construction and off-site fabrication.

3.5.4 Assembly Training with BIM

1. Advanced Construction Training through BIM

Virtual prototypes developed from the project BIM model can be used to train operators in the assembly of DfMA components, sub-assemblies and entire projects in a very safe and low-cost environment before they are allowed to enter the relatively higher-risk live environment of a site. This can help maximise the productivity of site personnel and facilitate the use of lower-skilled and/or multi-skilled gangs. A range of tools and outputs can be used to do this.

2. Exploded Axonometric Diagrams

An exploded axonometric diagram, sometimes known as an "Ikea" style diagram due to its extensive use by the furniture manufacturer and retailer, is a simple and easy to understand way to demonstrate the assembly technique for a component or series of components, including all the fixings and tools required.

3. Animations and Training Videos

Animations and training videos can be extracted from 4D BIM models that include time or construction sequence as a data set. These can be used to plan construction logistics as well as providing training for operators.

4. Immersive Walkthroughs

3D BIM models can be experienced as immersive walkthroughs through virtual reality (VR) headsets which are commercially available at increasingly affordable prices. These can be used for client and operator exploration of the facility to better understand the construction approach and design output. Walkthroughs can be generated of the finished model or as a snapshot of a point in the construction process. Walkthroughs can be self-guided or they can follow a predetermined route.

5. Training Guides

Outputs from the BIM model can be incorporated into hard or soft copy training guides for the use of operators. These outputs could include step by step assembly sequences, lifting strategies or method statements. The training guides that are developed will vary depending on the specific project requirements.

Exploring a walkthrough animation using virtual reality
(Image source: BCA)

3.5.5 Numerical Control and Serialisation

1. High-precision Fabrication through Numerical Control

On projects where highly detailed and data rich BIM models have been developed during the design stage, precise fabrication of components can be carried out through the use of automated machinery such as computer-numerically-controlled (CNC) machines. These machines interface directly with the BIM model to produce components closely matching the originally modelled design, either by conventionally fabricating or in some cases 3D printing the components.

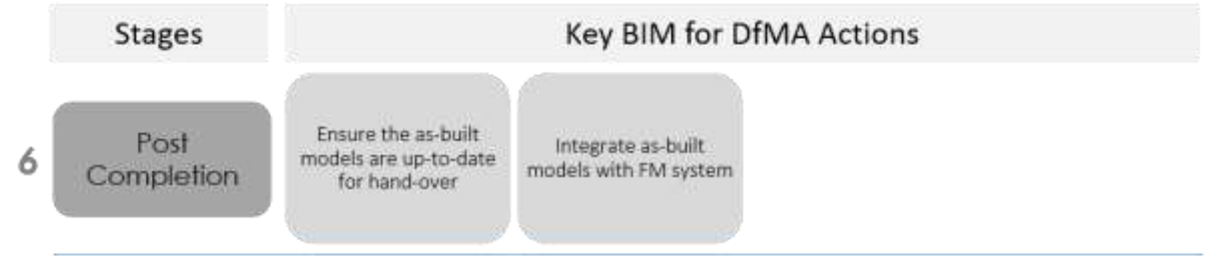
A computer file is outputted from the BIM model that is interpreted by a processor at the manufacturing facility into a series of operational commands which are fed into the particular CNC machine for fabrication. In the case of complex components, multiple CNC machines may be utilised to produce different elements which are combined into the finished component.

2. Asset Management using Serialisation

Asset management software makes use of physical QR coded tags which are attached to prefabricated building components. The tags include a QR barcode and an identification number. Each code is unique to its asset and identifies the asset in the cloud database. Asset attributes are uploaded to the cloud database. Field staff can then record any installation, maintenance, inspection or other event data via the mobile device interface. Captured on-site data is transferred to secured web-hosted servers which are accessible from anywhere in the world in real-time.

The cloud database can include spreadsheets, Word documents, PDF files and images to serve as a complete reference database for each asset. Documents can be instantly viewed on the field and always kept up to date.

3.6 Stage 6: Post-Completion



3.6.1 Maintenance

The benefits of BIM in terms of facility maintenance are just beginning to be realised. As-built BIM models can be used for tracking the life span and maintenance cycle of objects within the building, reducing the operational cost of the asset. Depending on the resources and capabilities of the project facility management team, either the BIM model itself or data extracted from it can be used. For a BIM model to be considered “as built”, it is important to ensure that it is kept up to date during the construction process, accurately reflecting the completed project including any changes that may have been made during construction. Standardised BIM data formats such as COBie are intended to facilitate more efficient communication of parametric information between construction teams and facility managers.

In addition to this, the use of standardised DfMA components has obvious benefits throughout the operational phase in terms of maintenance and replacement, for extending, refurbishing or reconfiguring assets, and also for re-purposing assets.

3.6.2 Contextualisation

The ability to identify and trace the source of individual DfMA components in the BIM model also allow the huge amount of data that can be created throughout the operational phase to be “contextualised” - if an asset is performing particularly well, the configuration of components can be analysed and lessons learned disseminated. If an asset is performing poorly or an element requires frequent maintenance, other components in similar circumstances can be sought and maintenance planning revised. Component replacement may be predicted through 4D simulation of asset operation with data values relating to maintenance regimes inputted into the BIM model.

3.6.3 Recycling and Reuse

During the demolition phase there is great potential for buildings constructed using standardised prefabricated DfMA components and assemblies to be “disassembled” rather than demolished, as safely as they are erected. These components and assemblies can potentially then be re-used on other projects. The information that is captured about these DfMA components in the BIM model can be valuable in planning deconstruction or dismantling of the elements. A disassembly strategy can be developed and tested in the BIM model simultaneously with the assembly strategy.

4 CASE STUDIES

4.1 Case Study 1: Crowne Plaza Changi Airport Extension

4.1.1 Introduction

The Crowne Plaza hotel extension at Changi Airport is a freestanding ten-storey building connected to the existing hotel building via a second floor linkway. The extension is around 10,000sqm and will add an extra 243 rooms to the hotel, bringing the total to 563. The extension is currently under construction by Dragages Singapore for the client, OUE Airport Hotel Pte Ltd. The extension was designed by architectural practice WOHA with structural engineers RSP and Surbana as mechanical and electrical engineers.

4.1.2 Construction Approach

The building was originally conceived as a traditionally built project but early in the process the design was modified to accommodate the potential use of a range of possible DfMA technologies. As part of their successful bid for the contract, Dragages proposed the use of prefabricated prefinished volumetric construction (PPVC) modules.

The PPVC modules were designed by specialist modular building supplier Unitised Building (UB). The modules were fabricated in a controlled factory environment in China, shipped to Singapore and delivered directly from the port to the site for installation at nighttime, minimising disruption to the road network and operating airport environment.

The design of the PPVC modules by UB was closely aligned with the design that had already been developed for the project. The adoption of PPVC on the project is estimated to result in up to 50% reduction in the construction programme and 75% reduction in required manpower on site compared to traditional construction.

Internal view of a completed typical PPVC hotel room module

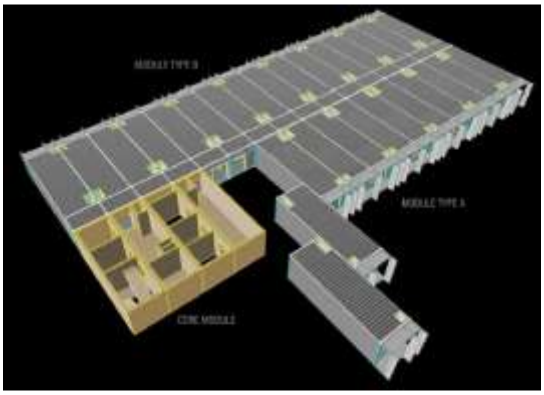
Artist's impression of finished building and existing hotel
(Images source: Dragages Singapore)

4.1.3 Design Considerations

The project was considered to be well suited to the adoption of a PPVC system. The efficient and repeated hotel room layout allowed a small grid of 3.2m to be established which was ideal for the volumetric units. All of the modular components (e.g. king and twin rooms, stair cores) were designed to fit within this standard grid. Support areas were situated on the ground floor which was traditionally built in concrete and created a podium structure for installation of the prefabricated modules. The design had to be frozen at an early stage to allow module fabrication to commence.

The prototyping stage was very important for the project, allowing stakeholders to inspect and approve the design and fit out of the modules while also allowing the system to be tested out and any issues resolved prior to full fabrication. Virtual prototyping of the model enabled renderings to be produced for client review and a full scale physical prototype of a hotel room module was built and inspected for the project. The prototype included external structure and facade treatments to ensure as many interfaces as possible were tested prior to fabrication.

View of site from Terminal 2 during PPVC module installation
(Image source: Dragages Singapore)



Arrangement of PPVC modules on a typical floor
(Image source: Dragages Singapore)

4.1.4 Design Coordination

The structural, mechanical and electrical engineering designs were developed as separate but coordinated BIM models in advance of the contract award. These were passed over to Dragages who used the BIM model for coordination of MEP services with the PPVC modules. The BIM model was also passed to UB for development of the connection details for the PPVC modules. 2D outputs of the module design were generated for design team approval.

4.1.5 Opportunities

The adoption of DfMA technologies on this project involved a shift in mindset and operational processes for all of the parties involved in the project. By adjusting working practices across the industry it will be possible to ensure that DfMA can take off in Singapore.

4.2 Case Study 2: Housing and Development Board West Terra @ Bukit Batok

4.2.1 Introduction

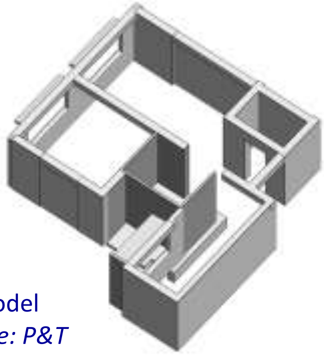
The HDB West Terra project at Bukit Batok comprises nine residential blocks with 1793 units in total, as well as two multi-storey carparks, associated retail and other amenities. Three of the nine residential blocks will be constructed using PVC (prefabricated volumetric construction) components. All of the nine blocks will also feature other DfMA components which are standard on HDB estates including PBUs (prefabricated bathroom units), precast flat panels, precast facade panels, precast stairs, precast vertical shafts etc. The West Terra project will be the first HDB project to utilise PVC components.

The project team comprises P&T Consultants (architects and structural/civil engineers) and Rankine & Hill (MEP engineers) and the contractor is Teambuild.

4.2.2 Benefits of BIM

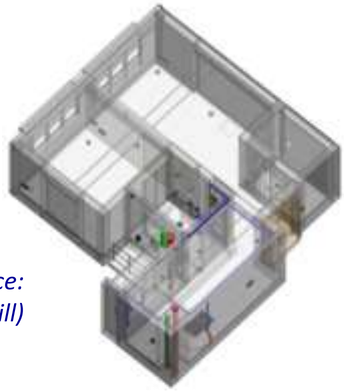
The project design was delivered by the consultants using BIM. This required a greater amount of design activity at the front end of the process in order to deliver greater efficiencies in the construction process. HDB understood this approach and as the project construction continues benefits are being realised including a reduction in the number of change requests, greater coordination between design disciplines and clash detection carried out in advance.

The BIM model also enabled the team to develop a thorough prefabrication strategy incorporating the PVC units, the standard HDB precast components, and the traditionally built elements of the project.

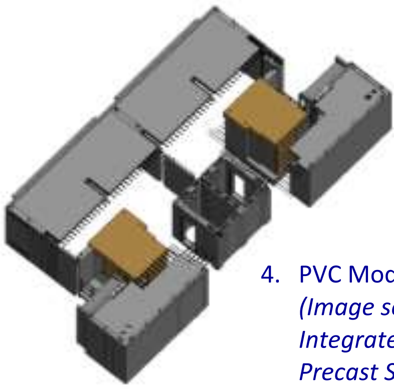


1. Structural Model *(Image source: P&T Consultants)*

2. Architectural Model *(Image source: P&T Consultants)*



3. MEP Model *(Image source: Rankine & Hill)*



4. PVC Model *(Image source: Integrated Precast Solutions)*

4.2.3 Project Challenges and Opportunities

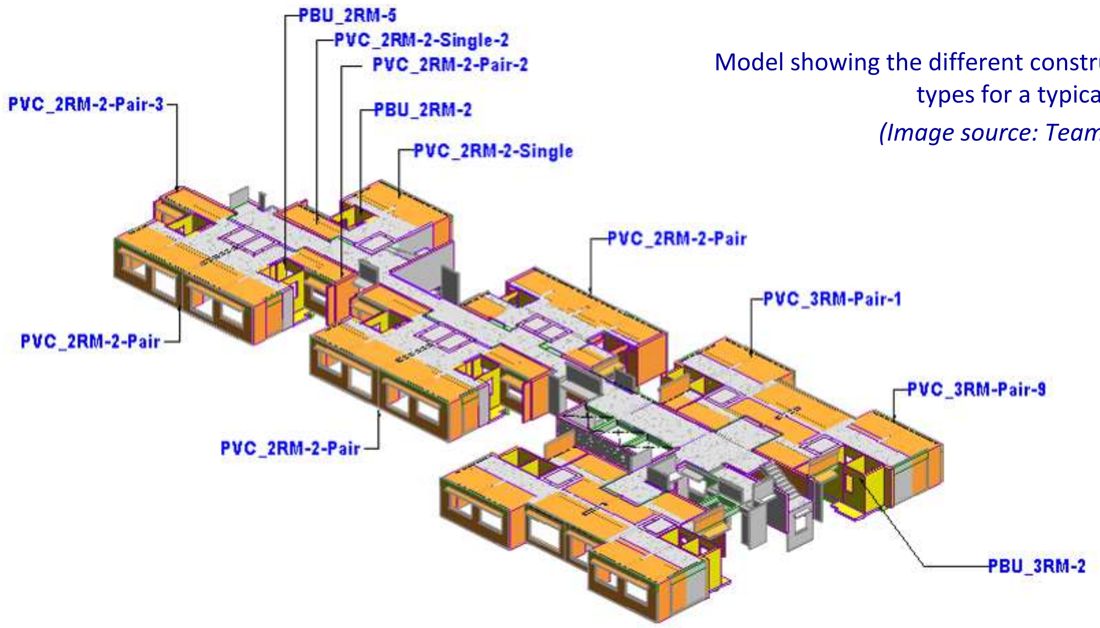
Due to time constraints on the project, some of the initial modelling work was carried out in AutoCAD and manually transferred into the BIM model at a later stage, Also, the structural analysis model was built as a separate model requiring manual coordination with the BIM model. To achieve a higher level of efficiency in design development, BIM models could be developed from the earliest project stages and duplication of information should be avoided where possible.

The design team also noted that additional resource was required during the design development to model the prefabricated components as Revit families. This is unavoidable where new components are being used for the first time but will lead to reductions in required resources on future projects using the same or similar components.

Teambuild also made a large investment in the fabrication of a custom built gantry crane for the project, with the overhead cost to be amortised over several projects. This crane was procured to allow lifting of the heavy concrete modules. The decision to invest in the crane was made after the contractor worked with the design team to analyse the load data in the developing BIM models, which made it clear that the bearing capacity of a standard tower crane would be insufficient.

The team noted that the overall design process using BIM worked very differently to a traditional project process. In particular, the client had to be prepared to accept an earlier design freeze and a reduction in design flexibility to suit the PVC modules due to the restrictions around the volumetric nature of the system. The DfMA approach is not a “one-size-fits-all” solution and different projects will require different strategies.

The design team put considerable effort into standardising the design as far as possible to facilitate adoption of PVC on the project. However, the final design still incorporated 12 variants of PVC module in order to meet the design requirements of the project. Consideration of the potential for standardisation on specific projects will inform the DfMA solutions that are selected.



Model showing the different construction types for a typical floor
(Image source: Teambuild)

4.3 Case Study 3: High Park Residences

Rendered image of project generated from the BIM model
(Image source: China Construction (South Pacific))

4.3.1 Introduction

The new High Park Residences condominium project near Sengkang is currently under construction and setting new standards for BIM adoption on residential projects in Singapore. The project consists of six residential towers and a low rise precinct set above a landscaped podium with basement car parking below. The client, Fernvale Development Pte Ltd (a Joint Venture between CEL Development Pte Ltd and Unique Residence Pte Ltd) is working with project managers Heeton Holdings. The builder is China Construction (South Pacific) Development Co. and the design team includes P&T Consultants (architects and structural engineers), United Project Consultants (services engineers) and Rider Levett Bucknall (quantity surveying).

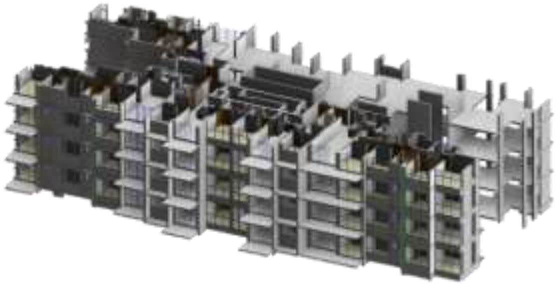
4.3.2 BIM Process

The project was designed by the consultant team in BIM from the start. Each discipline developed separate BIM models that were combined for coordination. The project was tendered and the contract awarded as a REDAS partial design and build contract. The project structural and services engineers were novated to the contractor and the architects were retained on the client side.

The contractor developed their own construction BIM model from scratch which is maintained in parallel with the design BIM models produced by the design team. All design coordination takes place in weekly ICE (integrated concurrent engineering) sessions. Changes are captured in the construction BIM model based on the weekly BIM coordination meeting. Shop drawings are produced from the construction BIM model and are approved for construction by the design team. All model sharing, information transfer and file collaboration takes place on the Autodesk A360 platform which serves as a central cloud-based repository for project information.

The project has adopted a “build twice” philosophy where the virtual BIM model is used for testing the construction approach prior to real world implementation on site. The BIM model is used to develop resource planning, construction methodology, build sequence, clash detection and immersive walkthroughs for client approval. The BIM model will be updated over the course of the construction project and handed over at “as built” status to the client upon project completion.

Detailed 3D axonometric view of apartment layout shown in the BIM model
(Image source: China Construction (South Pacific))



Detailed 3D axonometric view of apartment layout shown in the BIM model
(Image source: China Construction (South Pacific))

4.3.3 DfMA Adoption

The project is generally conventionally built however 60% of bathrooms are PBUs (prefabricated bathroom units).The decision to incorporate PBUs in the project was made at the design stage. The PBU supplier provided 2D design information which was modelled in the construction BIM model by the contractor. The PBU installation is on the critical path of the project and incorporating them into the BIM model as components allowed construction sequence and resource requirements to be better understood.

4.3.4 Conclusion

This project has adopted BIM techniques and workflows to a high degree and both the contractor and client see this as the way forward for their business on future projects. Both the contractor and client teams have recognised and are realising the benefits of BIM in improving project efficiencies and productive workflows. The client team hopes that adoption of BIM on future projects will allow different types of DfMA solutions to be considered, analysed and successfully incorporated into projects to achieve cost and time savings as well as higher levels of construction productivity.

3D axonometric view of a bathroom extracted from the BIM model
(Image source: China Construction (South Pacific))

BIM model used for services coordination
(Image source: China Construction (South Pacific))

4.4 Case Study 4: JTC LaunchPad @ one-north

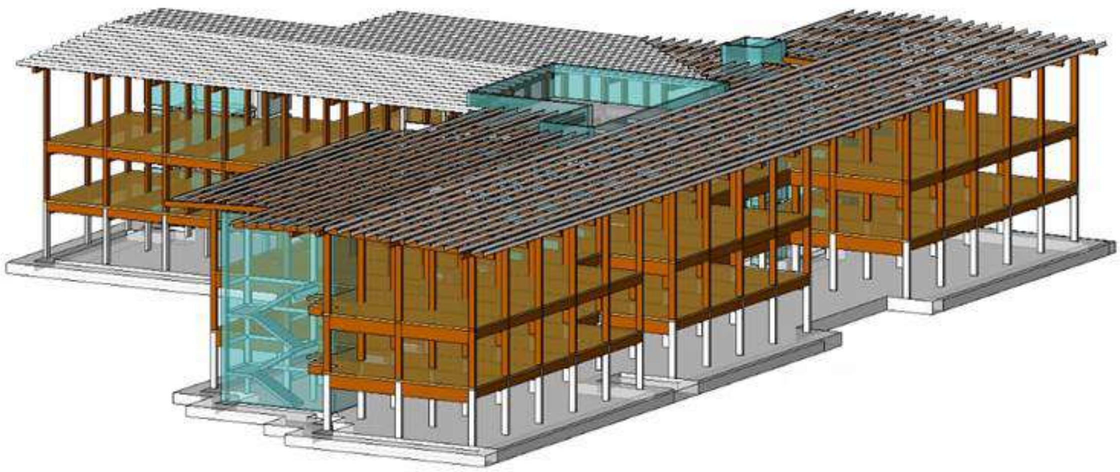
4.4.1 Introduction

Block 81 at JTC LaunchPad @ one-north is a new 3 storey building which will provide industrial workshop space for startup businesses. The original design incorporated a steel and precast concrete structure but the steel elements were subsequently changed to a CLT and Glulam (cross-laminated timber and glued laminated timber) structure. With potential savings in manpower as well as time required for construction, Industry Infrastructure Innovator JTC has undertaken the role to pioneer the use of this material in Singapore's built environment for workspaces. Apart from its potential to improve construction productivity, CLT and Glulam outperform conventional construction materials like concrete and steel in terms of environmental sustainability, reducing the carbon footprint of the development.

4.4.2 Project Team

The timber structure for the project was designed by the project structural engineers, Ronnie & Koh Consulting, whilst the structure is by the timber subcontractor Venturer Timberwork under the main project contractor Lian Ho Lee Construction. The fabrication design for the CLT and Glulam members was carried out by Venturer's partner Timber Concept GmbH, based in Germany. The timber members are being manufactured in Austria from sustainably sourced and certified spruce and supplied by Hasslacher Holzbausysteme GmbH and KLH Massivholz GmbH.

Venturer Timberwork has 20 years' history providing timber to the domestic construction market in Singapore, with several projects in Singapore and the region ranging from timber decking systems (Dekloc) to a bespoke "free-form" Glulam structure for the Shangri-La hotel.



BIM coordination model for the project
(Image source: Venturer Timberwork)

4.4.3 Design Process

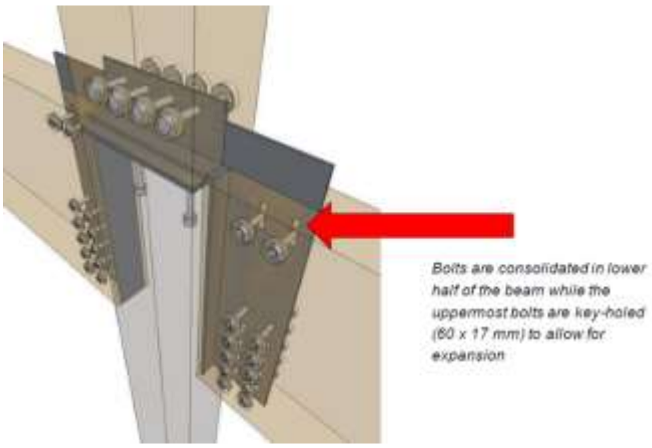
The project structural engineers, Ronnie & Koh, developed the structural model and timber specification for the project. This was converted into a Revit model by Venturer and Lian Ho Lee for coordination with the architectural and MEP models using BIM. The fabrication and connection drawings for the individual timber components were developed in hsbCAD by Timber Concept and approved by Venturer and Ronnie & Koh prior to fabrication.

4.4.4 Design Considerations

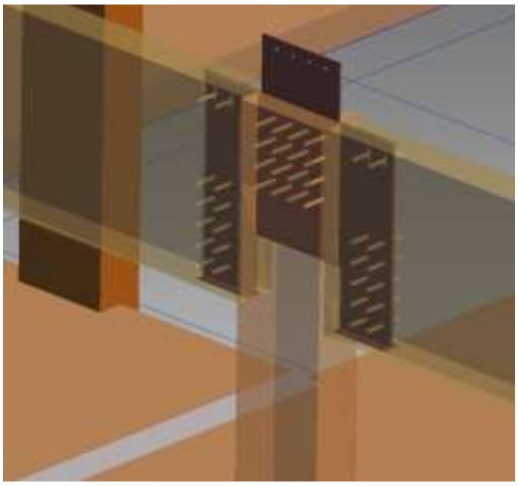
The interface between the timber and precast elements in the project had to be considered in detail. Steel connection plates were designed and these are fixed to the Glulam members and cast in place into the precast elements. As a result of this the manufacturing tolerance for the members was very small, maximum 10mm between interfacing members. The factory's manufacturing environment is highly controlled and the elements are fabricated directly from the hsbCAD model by precise CNC machines. Test reports, physical samples and certificates of conformity are all provided by Venturer, and the dimensional change of the timber due to moisture content was tested and found to be workable.

A challenge for the project has been the requirement to freeze the structural design early to allow the shop drawings for the timber members to be approved and released for fabrication. The intent of the project is to prefabricate as far as possible. To improve on-site productivity, the fabricators utilise precision engineering in the manufacture of their timber products. Since the members are manufactured in Austria in order to comply with Eurocodes, the early sign-off is required to allow sufficient time to ship the finished members to Singapore (approximately 6 weeks' journey).

Improved efficiency through prefabrication will result in significant time-savings in construction. This will in turn greatly reduce site labour and create an efficient and streamlined assembly approach. The construction of the foundation slab is currently underway and project completion is currently scheduled for the end of 2016.



Designing for movement at connection
(Images source: Venturer Timberwork)



Typical connection detail for Glulam members

4.5 Case Study 5: NTU North Hill Residence Hall

Artist's impression of NTU North Hill Residence Hall project
(Image source: P&T Consultants)

4.5.1 Introduction

The Nanyang Technological University's (NTU) North Hill Residence Hall project comprises six blocks of 13 storeys with 1673 student hostel rooms and apartments, of which 1661 will be built by the main contractor, Singapore Piling & Civil Engineering Pte Ltd, using the Prefabricated Pre-finished Volumetric Construction (PPVC) system designed by Moderna Homes Pte Ltd. The project also incorporates jump formed cores, precast stairs and traditionally constructed in-situ concrete elements. It is the first public high-rise development using PPVC to be built in Singapore.

Each PPVC module comprises a hot dip galvanised steel structure with factory applied finishes and will hold two rooms that can house one student each. The lead consultant and architect for the project, P&T Consultants Pte Ltd (P&T), used BIM to design and implement both the PPVC and the traditional construction elements for the project. CAD drawings were exported from the BIM model and used for fabrication.

The PPVC modules were fabricated at Moderna Homes' supply factories in Singapore, China, Taiwan and Malaysia, quality checked by Moderna Homes at the supply factory, shipped to the fit out yard in Jurong for finishing, and finally delivered to site for installation. Prefabricated AC ledges and balconies were attached to some PPVC modules prior to lifting. A small percentage of the finishing works were performed on site to seal the joints between the PPVC modules.

There were more than 10 main module types with several variants each. The repetitive modules allowed for parallel design and technical coordination to be performed without compromising on the overall aesthetics of the façade. Further reduction in the total number of variants produced at each fabrication facility would achieve even greater construction efficiencies.

The BIM model was used for collaboration between the different disciplines, design management, cost management, coordination of the design and construction works and construction planning.

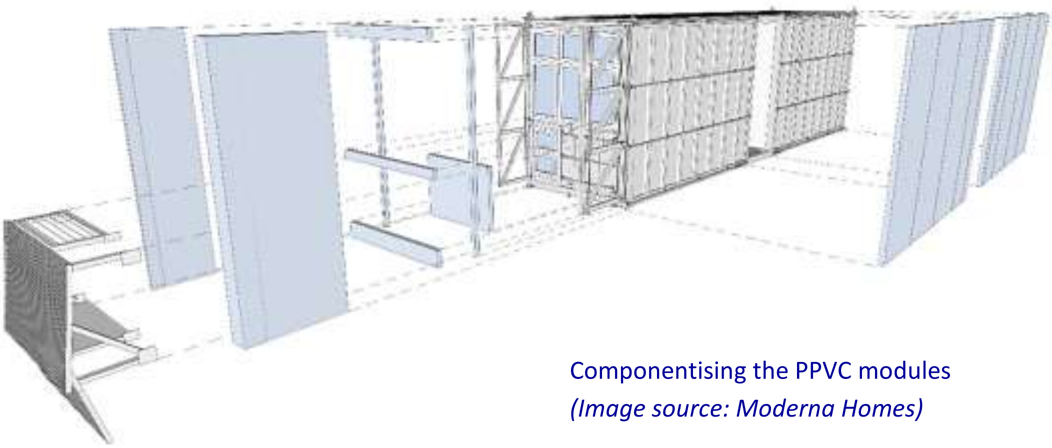
4.5.2 Objects Library

The PPVC modules were generated using BIM based on a set of library objects which P&T developed. BIM also enabled P&T to study, understand and visualise the assembly of the components and the interfaces between the modules, the external façades and the cast-in-situ works in 3D. Standardisation of components improved the consistency and clarity of the models. The modularity of the modules did not stop P&T from designing varied yet functional layouts with the PPVC modules. Standardisation also made quantification of building parts/materials and cost analysis easier. P&T were also able to build a repeatable methodology for linking the various BIM models of the PPVC modules together to make updates, minor changes and approval of contractors' shop drawings easier.

4.5.3 Work Processes

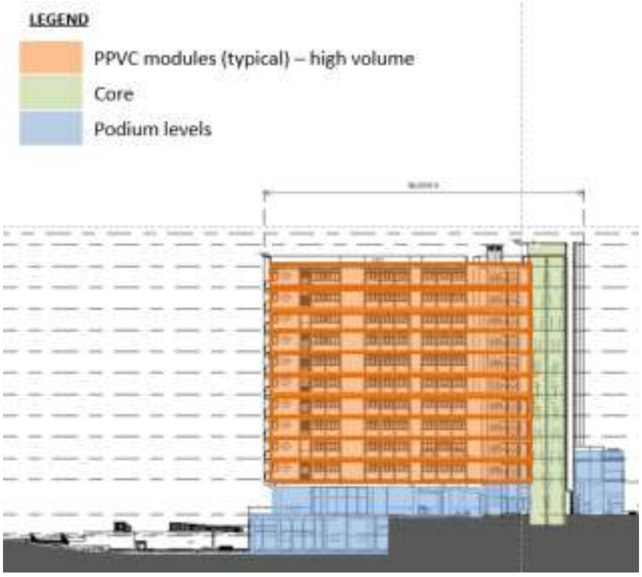
P&T developed an overall 3D BIM framework of models and families to compartmentalize the work scope and implement parallel work processes for the different parts of the project. This parallel on-site and off-site construction methodology increased the rate of production and enabled the team to plan and allocate resources more efficiently. Mr. Andrew Tan, CEO of BBR Holdings (S) Ltd, expects up to a 40 per cent increase in labour productivity and 15 per cent reduction in terms of the construction timeframe required for the project[2].

Mr Chew Teik Boon, Deputy Managing Director of Moderna Homes, noted that the cost and availability of space in Singapore to carry out the fit out works on the modules created a bottleneck in supply. The fit out could not be completed overseas due to import costs and availability of proposed finishes in overseas markets. Given that tiling contractors were already on site working in the cast in-situ areas, the PPVC installation could have been further accelerated by carrying out the PPVC tiling works on site as well. This would also avoid doubling up of trades in multiple locations.



Componentising the PPVC modules
(Image source: Moderna Homes)

[2] *The Business Times, BBR clinches $196m contract to build NTU student hostels, published 2 July 2014, http://www.businesstimes.com.sg/print/1164158*



Demarcation between PPVC and conventional construction
(Image source: P&T Consultants)

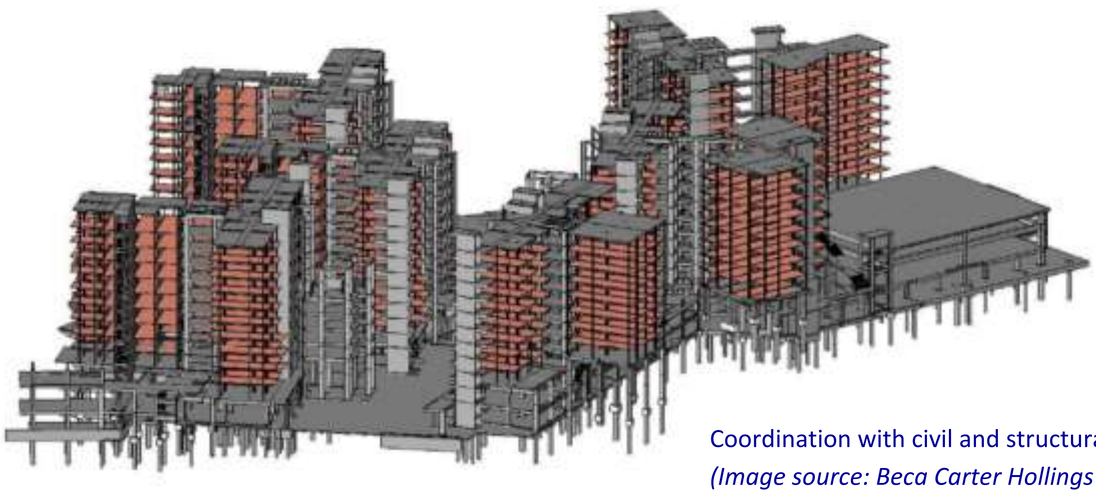
4.5.4 Coordination

As the overall project had both PPVC and conventional construction elements, BIM provided an ideal platform for the coordination of the different disciplines for the project at the module, block and overall project levels.

Using a hybrid approach of PPVC and cast in-situ works also posed a challenge for the team especially in the interfacing between the two different forms of construction.

The finished level of the PPVC modules which included the common corridor had to be accurate when installed, aligning precisely with the finished floor level of the lobby and staircase core which was cast in-situ and connected to the corridor. In this case, the height of the PPVC modules was fixed and the cast in-situ works took reference from the PPVC modules.

The technical coordination and integration of the off-site assembly of PPVC parts and on-site installation of the modules was further eased through the use of BIM.



Coordination with civil and structural design
(Image source: Beca Carter Hollings & Ferner)

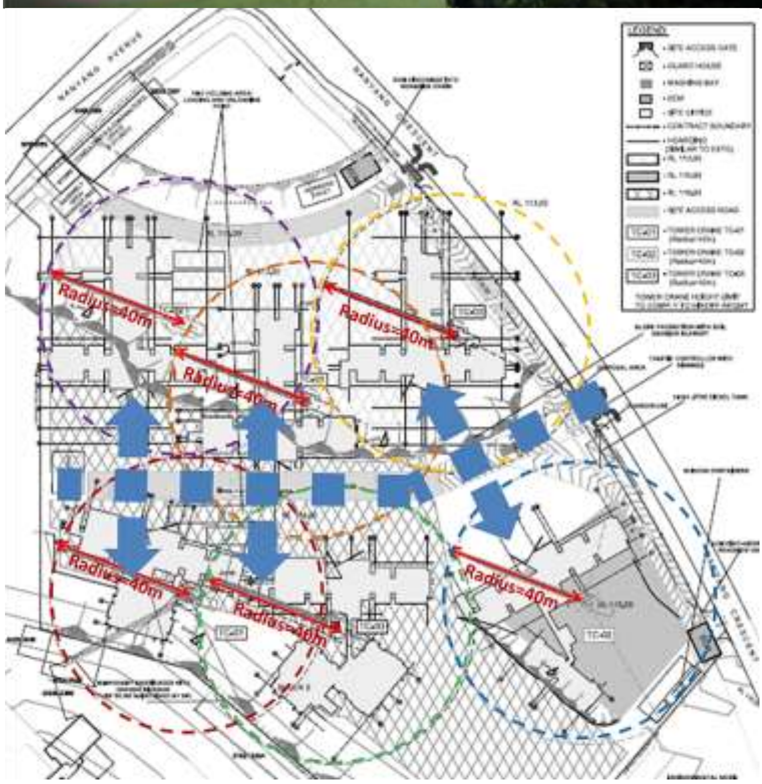
4.5.5 Construction Planning & Scheduling

BIM enabled P&T to work closely with the contractors to plan the hoisting and operations of the tower crane for the PPVC modules. Monitoring and tracking of the fabrication, assembly, delivery and installation using BIM sequencing and scheduling helped the Contractor to manage inventory on and off-site more effectively.

4.5.6 Off-Site Fabrication

The Contractor produced drawings in CAD for fabrication off-site, and returned paper drawings to P&T for comment and approval. As supply chain BIM adoption is on the rise it is expected that fabricators will be increasingly capable of fabricating directly from BIM models, ensuring greater coordination, quality and consistency. Moderna Homes plans to increase their BIM capability and become an early adopter of the technology.

Construction planning and sequencing in BIM
(Image source: Singapore Piling & Civil Engineering)



Planning the PPVC module hoisting operations
(Image source: Singapore Piling & Civil Engineering)

4.5.7 Site Designed for Delivery and Installation

The hard-standing for the fire engine access designed for the site was also used to transport the heavy equipment and the PPVC modules to site. Three high capacity tower cranes were used instead of mobile cranes to hoist the PPVC modules into place on site.

The BIM models were used to determine the locations of the tower cranes to optimise the reach for hoisting and installation of the PPVC modules on site. The installation of each PPVC unit took up to 40 minutes and 12 operators, including the provision of temporary safe working platforms. The three tower cranes were each capable of installing up to 8 PPVC units per day.

Moderna Homes estimated that the use of the PPVC system reduced the number of required vehicle movements by almost two thirds, from approximately 3000 total truck trips to just over 1200. This was a major advantage in terms of cost and logistics.

P&T noted that early involvement and consultation with the specialist sub-contractor was crucial to developing the PPVC strategy for the project. Understanding the fabrication process for the PPVC modules and getting their inputs at the onset of the design phase helped the consultants to better incorporate the considerations and constraints into their design. BIM further enabled the design to construction process to be more coordinated and the fabrication off-site to be better controlled.

4.5.8 Conclusion

The NTU North Hill Residence Hall project is on-track to become an early success story in Singapore's DfMA journey. The use of BIM was integral in ensuring the successful design and delivery of the DfMA elements of the project. Greater standardisation of components will help to ensure even greater benefits on future projects. As BIM capability increases across the entire supply chain, Singapore will be even better placed to deliver successful projects using DfMA.

Fabrication of the PPVC modules
(Images source: Singapore Piling & Civil Engineering)

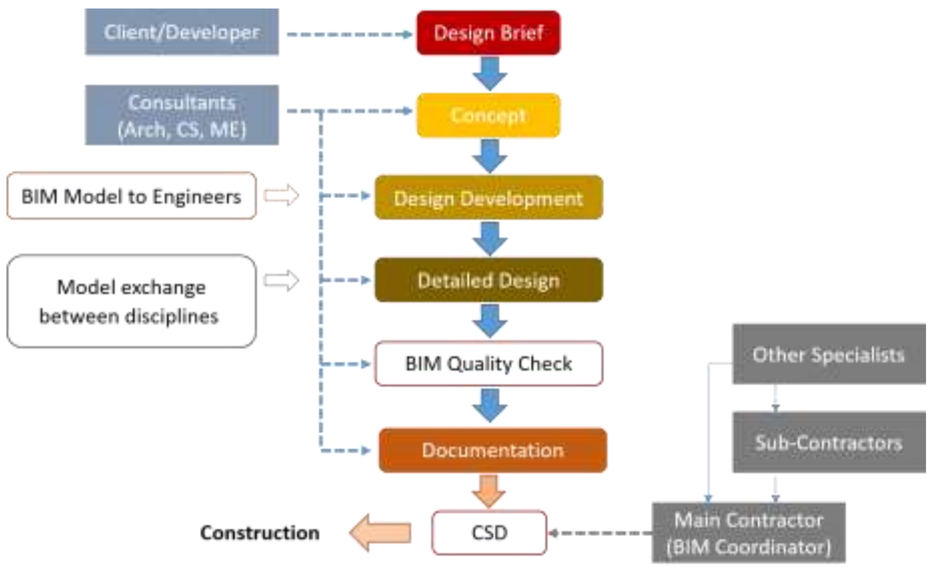
APPENDIX 1: HDB WEST TERRA @ BUKIT BATOK USE CASE

Introduction

This Appendix is intended to demonstrate how BIM was used to drive the adoption of DfMA approaches on the HDB West Terra @ Bukit Batok project throughout the various project stages.

1 Project Brief Development

The project was designed using HDB's existing catalogue of standardised precast components including the wall panels, stairs, chute and household shelters. In addition, three of the blocks utilised not only PBU modules but also PVC modules, the first HDB project to do so. The design and construction process had to be changed and BIM was used innovatively to support the design, fabrication and manufacturing processes.



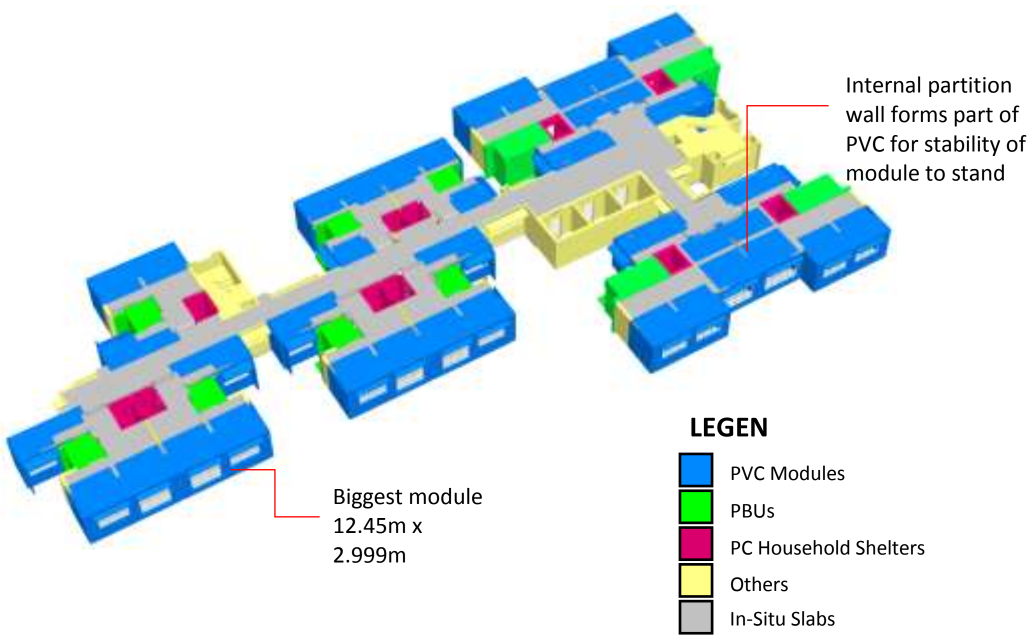
Typical BIM workflow for a design and build DfMA project
(Image source: Teambuild)

2 Conceptual Design

The initial models developed at conceptual design were used to provide visualisations and for orientation and spatial studies. 2D and 3D outputs generated from the models also allowed for rapid exploration of various design options. Project data such as floor area and schedules extracted from the models were used as references to further develop the DfMA approach and fine tune the design concept.

The conceptual model of the overall development was used to determine the general arrangement and identify the typical units and floors of the development.

The typical units were further componentised into precast components, PVC and PBU modules. Early involvement of the main contractor and specialist sub-contractors provided valuable inputs on the PVC modules such as the optimum dimensions and weight of the modules for ease of fabrication, delivery and assembly. Standard precast parametric components from HDB's object library were also incorporated.



Standardising and modularising typical units
(Image source: P&T Consultants)

3 Detailed Design Development

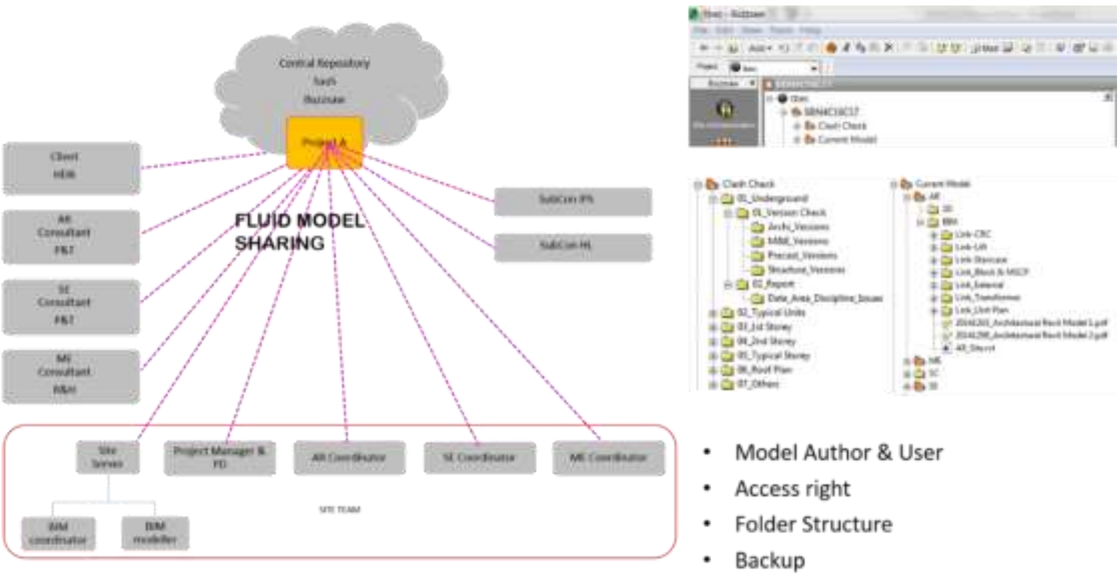
Model Structure & Setup

Part models were developed for the PVC and PBU modules. These were linked up to form the main model, including the precast components from HDB's objects library. As the precast components are parametric, dimensional changes are possible to suit the design needs. Uisng worksets and links enabled the team to work on the models simultaneously. Models were shared in a central repository for collaboration amongst the project team members including the specialist sub-contractors.

Detailed Design Considerations

Models were developed in more details incporating considerations such as the following:

- Detailed design and positioning of the PVC modules for stability, watertightness, ease of transportation, hoisting and installation on site;
- Optimized dimensions and weight of the PVC modules that could be lifted efficiently, taking into account the capability of the lifting cranes, type of cranes that could be used in the factory and on-site, the appropriate type of lifting gear etc.;
- Connection and joint details between the PVC and PBU modules and the different precast components;
- MEP provisions e.g. drainage for the shallow traps and wall hung WCs and location of the shaft for future maintenance access.



- Model Author & User
- Access right
- Folder Structure
- Backup

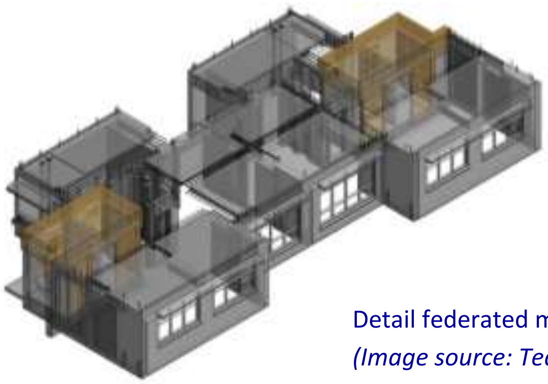
Model structure and sharing setup
(Image source: Teambuild)

3 Detailed Design Development

Structural Design Considerations

The unconventional connection details particularly between the different precast modules posed a challenge to the design. Starter bars from the PVC and PBU modules and pour strips in between the precast modules had to be introduced to ensure continuous load transfer to the vertical structural members. Recess with slot holes to facilitate accurate levelness and vertical alignment between the PBUs were also introduced. The details were modelled in BIM and this gave the project team a better visualisation of the precast modules and plan for the integration of these modules with the construction process subsequently.

The structural design consultants also worked with the precasters to better understand the factory fabrication process and the on-site installation sequence and additional design checks were developed for the temporary stages of the construction process.



Detail federated model of PVC & PBU modules
(Image source: Teambuild)

3 Detailed Design Development

Coordinated Models

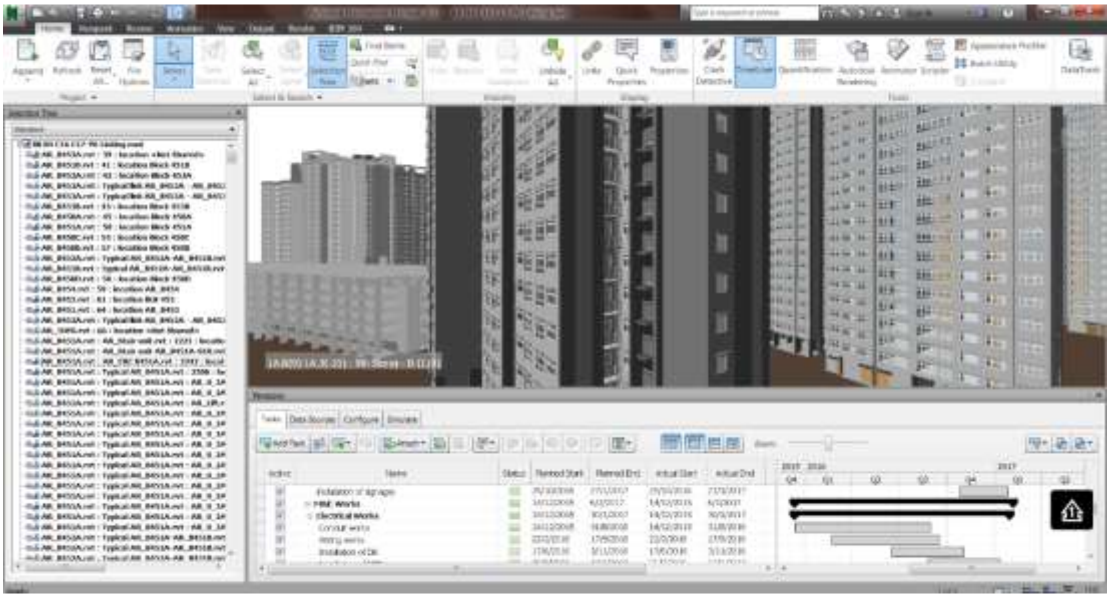
The specialist sub-contractors created the detailed models for the PVC and PBC modules. These were coordinated separately and then combined with the main model for the overall coordination for all the disciplines before fabrication drawings were produced.

Clash detection workspace showing model federation, identified clashes and resolution status *(Image source: Teambuild)*

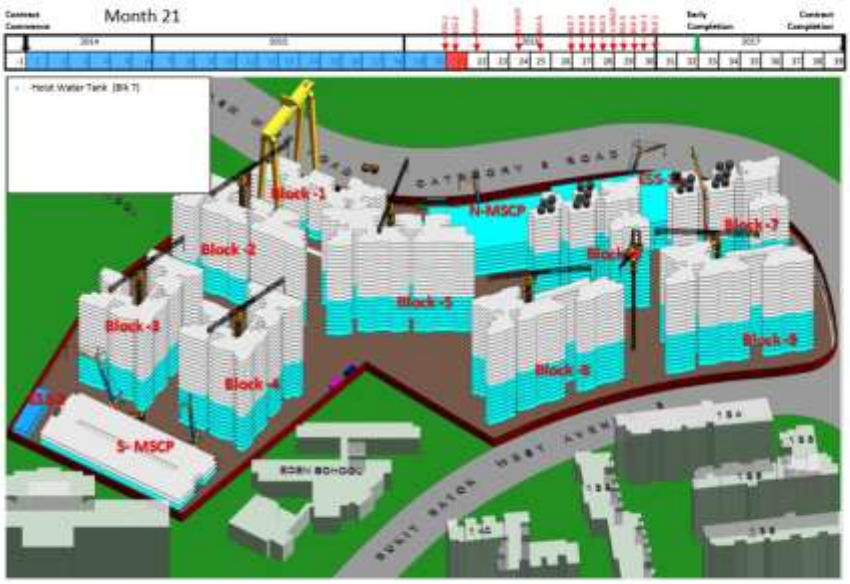
4 Pre-Construction

Simulation & Scheduling

The construction process was simulated using BIM to plan the activities. A direct link between the construction programme and the BIM allowed for greater integration of the on-site and off-site activities. The fabrication and delivery of the various precast modules and components were also incorporated into the programme.



Construction programme linked to model for scheduling
(Image source: Teambuild)



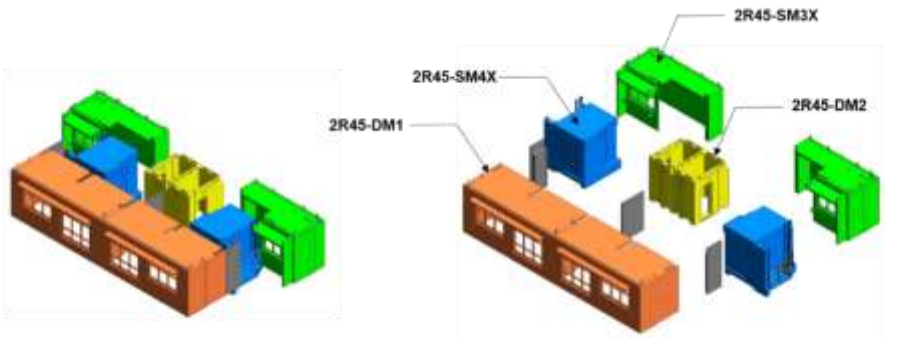
Simulation for construction sequencing and planning
(Image source: Teambuild)

4 Pre-Construction

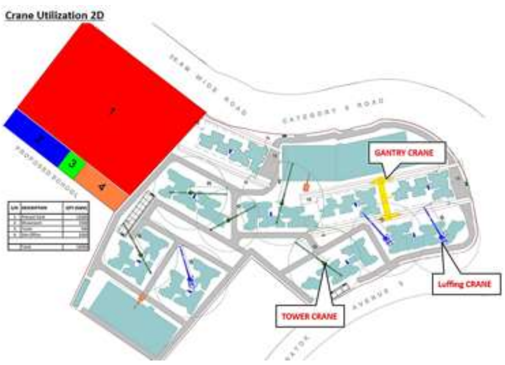
Construction Planning

The construction process was re-engineered to suit the use of PVC modules on the project. With BIM, the contractor and the specialist sub-contractors were able to plan for the logistics of the cranes and lifting activities both on-site and off-site, depending on the size and weight of the PVC modules. The type of crane to use and its deployment on site, the appropriate lifting gear for the various PVC modules and the maximum height for lifting etc. taken into consideration during design stage were further incorporated into the more detailed planning of the construction process. As the crane specialists were involved during the design stage, this allowed the modules to be bigger in size and heavier.

The hoisting and resouces required for the activity were also simulated and studied using the BIM model.

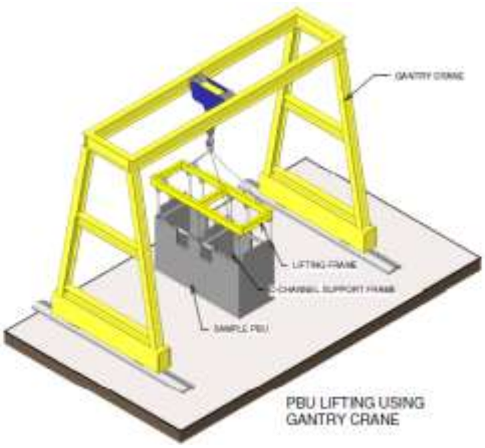


Description	Dimension (L x W x H)	Weight of Component	Weight of Lifting Gear	Estimated Total Weight	Number of Lifting Point	Factor of Safety
2R45-DM1	12450 x 2700 x 2800	31.18T	3 + 0.21 + 0.035 + 0.2 = 3.4T	31.18 + 3.4 = 34.58T	6	1.45
2R45-DM2	3150 x 2400 x 2800	11.28T	1 + 0.18 + 0.2 + 0.002 = 1.4T	11.28 + 1.4 = 12.65T	6	3.95
2R45-SM3X	5625 x 2750 x 2800	16.47T	1 + 0.18 + 0.2 + 0.002 = 1.4T	16.47 + 1.4 = 17.87T	5	2.80
2R45-SM4X	2930 x 2475 x 2800	9.39T	1 + 0.18 + 0.2 + 0.002 = 1.4T	9.39 + 1.4 = 10.79T	4	4.63



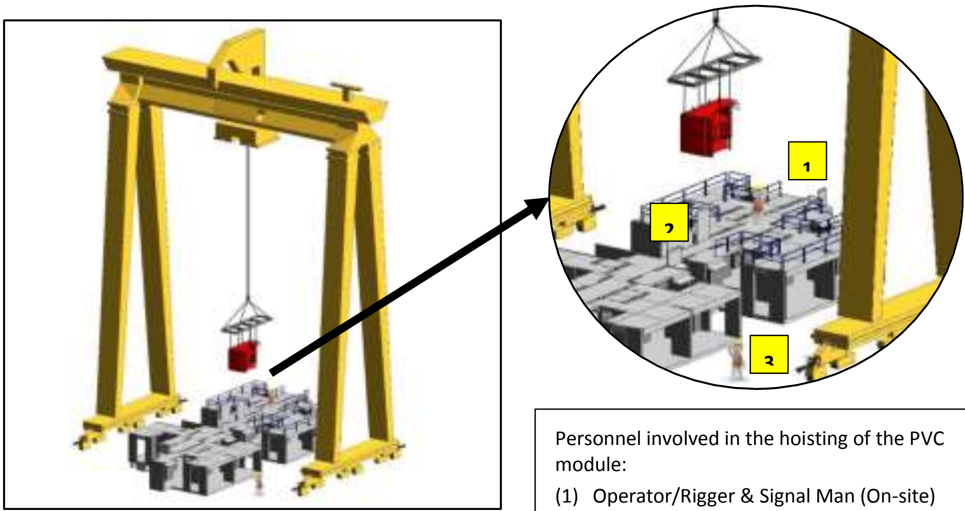
Lifting plan for the PVC modules of different sizes and weight
(Images source: Teambuild)

APPENDIX 1: HDB WEST TERRA @ BUKIT BATOK USE CASE



Description	Low Loader	PPVC/PBU Module	Remarks
Width	3m to 3.6m	3m to 3.4m	
Length to carry loads	5.5m	Max 14m	
Height	3.005m	Max 3.15m	
Capacity	Est 50.25 Ton	Max 33 Ton	

Sample view of lifting plan of gantry crane at the factory
(Image source: Teambuild)



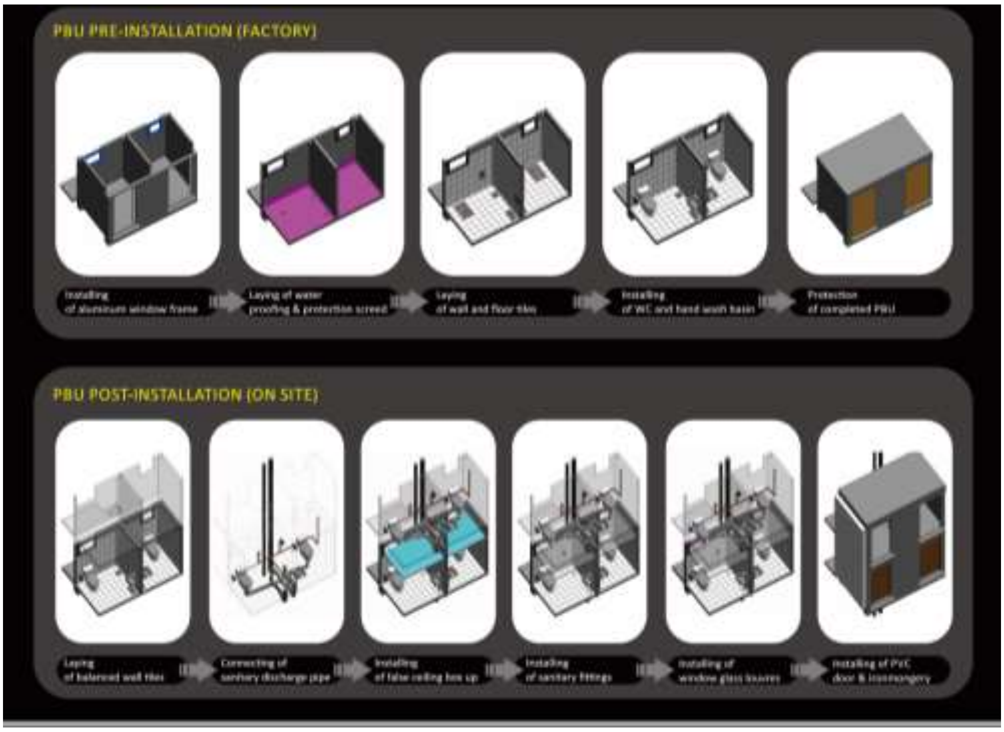
Personnel involved in the hoisting of the PVC module:
(1) Operator/Rigger & Signal Man (On-site)
(2) Lifting Supervisor
(3) Rigger & Signal Man (Precast Storage Area)

Planning the hoisting of PVC module for actual installation using BIM
(Image source: Teambuild)

4 Pre-Construction

Sequencing of Works

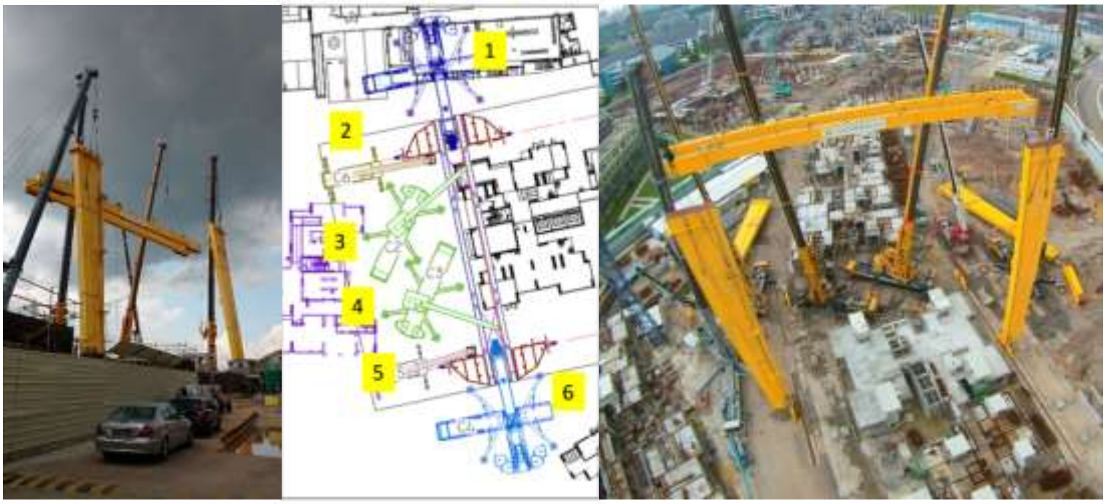
BIM was used extensively to plan the sequence of works for the PVC and PBU modules off-site as well as the installation and lifting activities of the modules on site.



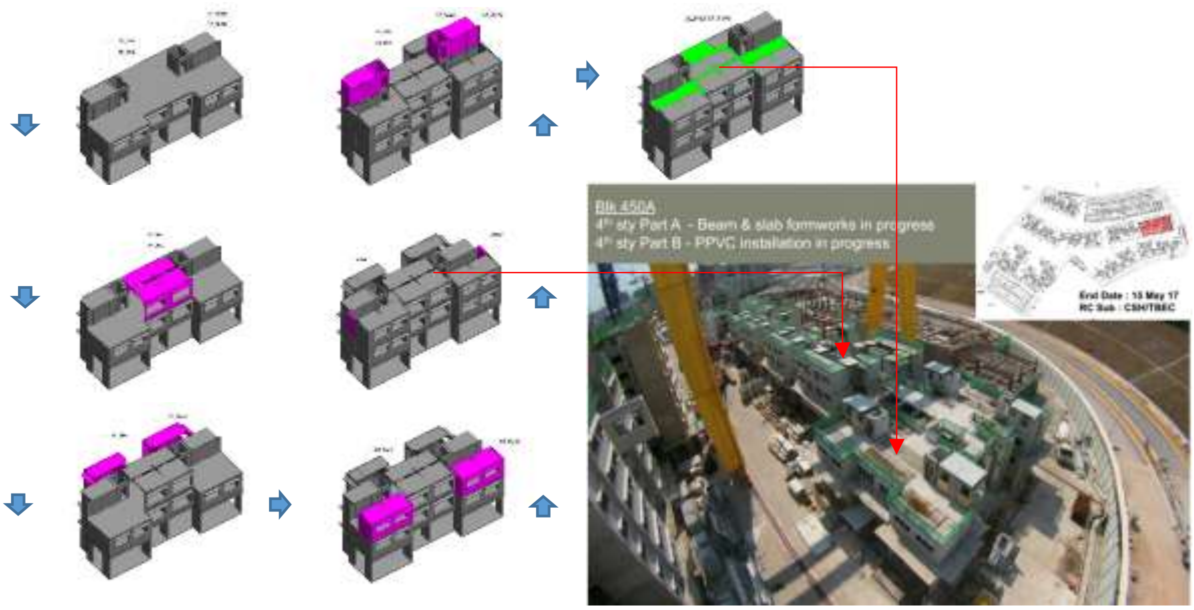
Sequence of works off-site and on-site for the PBU modules
(Image source: Teambuild)

5 Construction

The planned sequence of the fabrication and installation activities for the PVC and PBU modules was translated from virtual to actual execution on site.

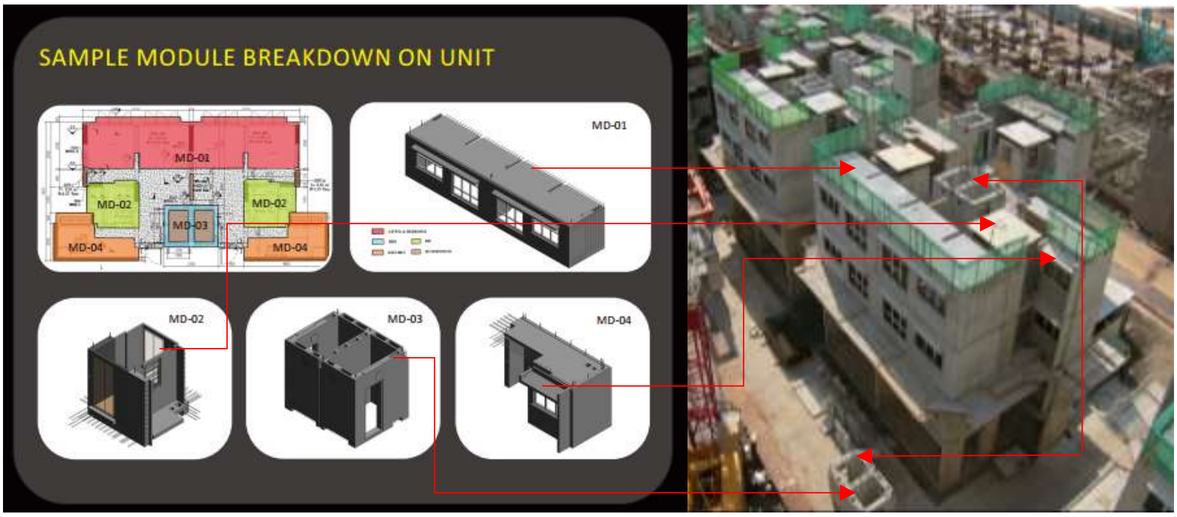


Erection of gantry cranes on site as planned
(Image source: Teambuild)



Planned sequence of installation of PVC modules versus the actual manufacturing and assembly on-site
(Image source: Teambuild)

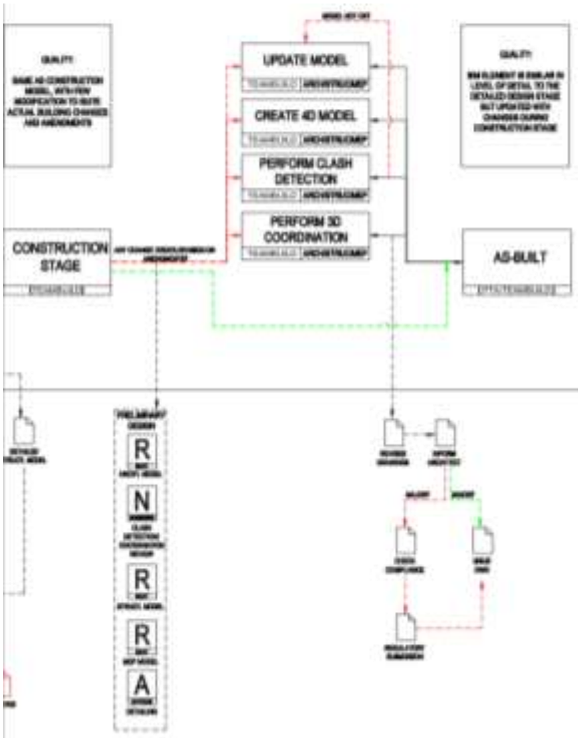
APPENDIX 1: HDB WEST TERRA @ BUKIT BATOK USE CASE

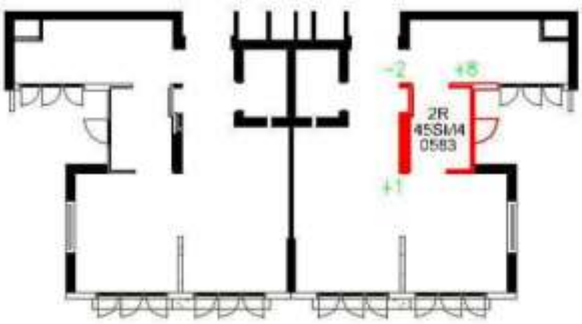


BIM models of the PVC and PBU modules for a typical unit as installed on site
(Image source: Teambuild)

6 Post-Completion

The as-built model development was included in the project's BIM Execution Plan right from the start. The central repository enabled the team to keep track and update the models as and when required, in particularly the module alignment, during the construction stage.





Screen shot of the process for as-built model development (left) and the model updated to reflect the actual alignment of module on-site (top)
(Images source: Teambuild)

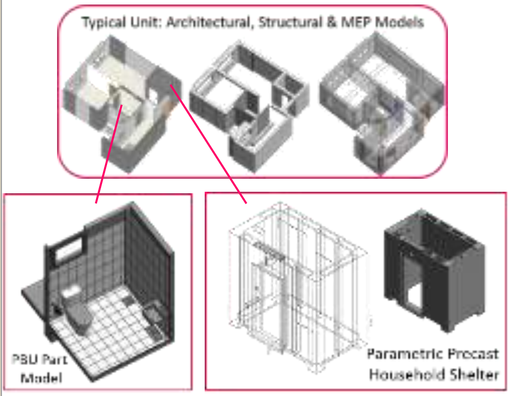
QUICK REFERENCE

This section summarises the typical BIM process and some of the key considerations in using BIM to integrate design, manufacturing, construction and asset management for DfMA.

STAGES	BIM PROCESS	CONSIDERATIONS
1. Project Brief Development	• Develop the DfMA strategy based on sector, availability of known products or suppliers, likely degree of repeatability, site/logistical constraints, project scale/value etc. • Establish BIM strategy to facilitate DfMA • Identify BIM outcomes & data extraction requirements.	• Ability of team to use BIM for DfMA. • Level of resolution and types of data to be built into model at each stage.
2. Concept Design Development	• Create conceptual model. • Standardise grids & layouts. • Identify repetitive modules and create parametric "placeholder" objects for the elements/modules.  Modular grids & layout  Repetitive modules *(Images source: P&T Consultants)*	• Early involvement of specialist contractors – inputs on off-site fabrication & on-site assembly. • Technologies to adopt e.g. PPVC, PBU, CLT/GLULAM etc. • Use of standard components. • Freezing of design as early as possible.

QUICK REFERENCE

STAGES	BIM PROCESS	CONSIDERATIONS

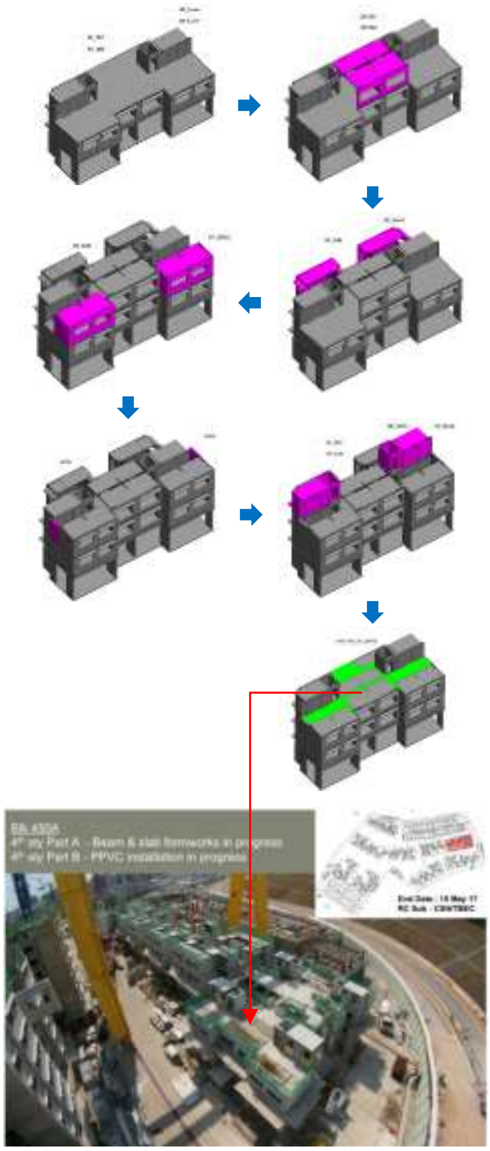
3. Detailed Design Development	• Develop library of parametric components & modules.
	• Develop detailed layouts & models/part models for the 3 disciplines.
	• Develop detailed connections/interfaces between components/modules and with conventional works.
	• Perform coordination/clash detection between modules, interfaces, intra- and inter-disciplines and overall model.
	
	
	Detailed part models & parametric modules *(Images sources: HDB, P&T Consultants & Teambuild)*
		• Model structure, linking strategies & change management.
		• Components library – modular, parametric, reusable, non-geometric attributes to be incorporated for various downstream uses e.g. costing, asset management etc.
		• Design considerations (not exhaustive):
		  ○ Optimal dimensions & weight of components/modules for delivery, hoisting & assembly;
		  ○ Connection & joint details – structural requirements, performance criteria (e.g. fire resistance, stability), interfaces, water tightness, production and erection tolerances etc.;
		  ○ Accessibility for installation & maintenance.
		• Collaboration & coordination methodologies & process.

QUICK REFERENCE

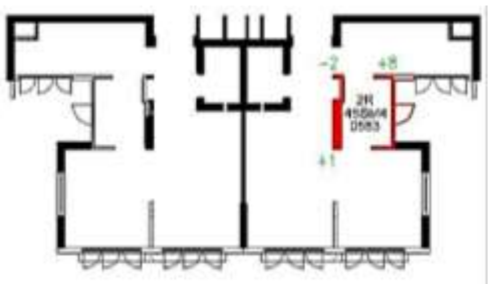
<table>
<tr><th>STAGES</th><th>BIM PROCESS</th><th>CONSIDERATIONS</th></tr>
<tr><td>4. Pre-Construction</td><td>Incorporate detailed information and validate/test – fabrication & assembly.
Plan construction activities – create virtual building simulations, plan scheduling & sequencing of activities for delivery, hoisting and assembly of components/modules on site.
Carry out virtual building and prototyping exercises using digital model – conduct training, refine construction approach, test feasibility and maximize site efficiency with digital model.
Create physical prototypes, first run studies, if necessary.

Planning logistics & crane utilization
(Image source: Teambuild)</td><td>Provisions and design for temporary supports, if any.
Fabrication & installation of components/modules – sequencing of works at fabrication yard offsite and/or within site, automation, installation sequencing etc.
Delivery, hoisting & installation – site constraints, transportation limits, capacity & launching location of cranes, impact to overhead structures & neighbouring properties.
Integrating fabrication & assembly with BIM.</td></tr>
</table>

QUICK REFERENCE

STAGES	BIM PROCESS	CONSIDERATIONS
5. Construction	• Manage and monitor logistics and allocation of resources on site. • Manage and track delivery & storage of components/modules e.g. via serialization/QR coding through each step of manufacturing, packing, logistics and delivery – data input into model to manage organization of components and logistics of site assembly process. • Validate installation on site & update models.  Actual assembly of PVC modules on site	• Optimising scheduling & tracking – fabrication, delivery & installation of components/modules. • Fabrication – assembly line, automated machinery, prototyping, training. • Technologies for tracking & validation on site – e.g. serialization, RFID, 3D scanning. Virtual design & planned sequence for the PVC modules installation *(Images source: Teambuild)*

QUICK REFERENCE

STAGES	BIM PROCESS	CONSIDERATIONS
6. Post-Completion	• Up-to-date as-built model(s) including all installed systems with operational data sets • Integrate BIM with building management system to manage operations – life cycle costs  Model updated to reflect actual module alignment *(Image source: Teambuild)*	• Information to be extracted from model for assets management • Reuse & Recycle - disassembly

REFERENCES & FURTHER READING

BCA Publications

BCA CONQUAS Enhancement Series:

- Good Industry Practices - Precast Concrete Elements
- Good Industry Practices - Prefabricated Bathroom Unit (PBU)

BCA Buildability Series:

- Guide to Precast Concrete and Prefabricated Reinforcement for Buildings, May 1997
- What You Need to Know About ….. Prefabricated Bathroom Unit (PBU), October 2012
- Modular Construction, March 2000
- Buildable Solutions for Landed Residential Development in Singapore, 2003
- Buildable Solutions for High-Rise Residential Development, 2004
- Reference Guide on Standard Prefabricated Building Components
- Structural Precast Concrete Handbook (2nd Edition)

Singapore BIM Guides:

- Singapore BIM Guide Version 2
  https://corenet.gov.sg/media/586132/Singapore-BIM-Guide_V2.pdf

- BIM Essential Guide for BIM Adoption in an Organisation
  https://corenet.gov.sg/media/586143/Essential-Guide-Adoption.pdf

- BIM Essential Guide for BIM Execution Plan
  https://corenet.gov.sg/media/586149/Essential-Guide-BEP.pdf

- BIM Essential Guide for Architectural Consultants
  https://corenet.gov.sg/media/586146/Essential-Guide-Archi.pdf

- BIM Essential Guide for C&S Consultants
  https://corenet.gov.sg/media/586152/Essential-Guide-CS.pdf

- BIM Essential Guide for MEP Consultants
  https://corenet.gov.sg/media/586155/Essential-Guide-MEP.pdf

- BIM Essential Guide for Contractors
  https://corenet.gov.sg/media/586158/Essential_Guide_Contractor_revised_7_Aug.pdf

- BIM Essential Guide for Collaborative Virtual Design and Construction
  https://corenet.gov.sg/media/1588655/bim-essential-guide-for-collaborative-virtual-design-and-construction.pdf

- BIM Essential Guide for Transfer of BIM into Building Performance Analysis (BPA) Tools
  https://corenet.gov.sg/media/1588649/essential-guide-bim-to-bpa.pdf

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	WITHIN EACH DISCIPLINE	ACROSS MULTIPLE DISCIPLINES	ALL DISCIPLINES
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For C&S Consultants	●		
For M&E Consultants	●		
For Contractor	●		
For BIM Execution Plan		●	
For BIM Adoption in an Organization			●
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