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Product Planning of Manufactured Construction Products

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A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

April 2019

Abstract

The construction industry is experiencing further industrialisation to achieve greater efficiency and flexibility in the development of manufactured construction products. The development of these products poses challenges because of new complex design requirements and manufacturing processes. There is therefore a need to develop product planning methods that can effectively address these challenges.

This research aims to develop product planning methods for complexity management of manufactured construction products. A framework for product planning for manufactured construction products is proposed, which involves application of methods for requirements management and modularisation.

Using a reverse engineering approach, the Quality Function Deployment (QFD) method was applied to a modular plantroom to model and analyse its requirements. The plantroom QFD model facilitated a deeper understanding of requirements analysis than existing practice at the collaborating company. The QFD method was subsequently applied to a whole modular apartment building to analyse its requirements and investigate how requirements flow down across hierarchical levels. The application showed that a series of connected QFD models support requirements analysis by allowing to investigate systems structure, traceability and data analytic solutions of complex building systems. The QFD models were evaluated and validated by engineers at the collaborating company and were found to be effective at capturing and analysing requirements. QFD is a powerful requirements analysis method for manufactured construction products because it offers a more systematic, holistic and structured approach to requirements analysis than those currently adopted in the industry.

The research also investigated the development and application of a multi-driver modularisation approach for manufactured construction products. The approach uses and integrates three modular tools, namely Dependency Structure Matrix, Modular Identification Matrix and Generational Variance Indexes, which support the design of flexible product systems. The approach is able to address multiple modularisation drivers and provide valuable design information.

Keywords: Product planning, complexity management, systems engineering, industrialised construction, requirements analysis, and modularisation.

Declaration of Originality

This is to certify that I am responsible for the research in this thesis and that the originality of work is my own except for where specified. This research was conducted at Imperial College London between April 2015 and April 2019.

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April 2019

Copyright Declaration

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Acknowledgements

The completion of this thesis was made possible by the support, guidance and encouragement of many people.

I would like to express my sincere gratitude to my project supervisor, Dr. Marco Aurisicchio, for his valuable guidance and generous support that enabled me to complete this challenging project. His knowledge, understanding and valuable time given to me during the course of this research are very much appreciated.

I am also thankful to Professor Jennifer Whyte for her valuable guidance and support, and to my industrial supervisors at Laing O'Rourke, Ireneusz Starzyk and Massimiliano Sfragara, for their assistance for the completion of the research.

The PhD program and research could not have been completed without the financial funding from the Engineering and Physical Sciences Research Council (EPSRC) and from Laing O'Rourke through Industrial CASE Award No:1589417. I am grateful to the ESPRC and Laing O'Rouke.

I would also like to acknowledge the contribution of Laing O'Rourke's engineering, design and research teams for their guidance and cooperation throughout the research. In particular, Adam Locke, Hugh Bowerman, Sam Murphy, James Potter and many others who have given their time and assistance.

I am thankful to my colleagues and friends at Imperial College London for their encouragement throughout the PhD process.

Dedication

I would like to thank my family for their unconditional support and encouragement. I am most grateful to both my parents and sister for the support they have given me throughout my academic life.

Ph.D. Publications

The following peer reviewed conference papers were published during this PhD research.

1. ***A Product Planning Framework for Mass-Customisation in Construction.***
   Wee, T.P.Y., and Aurisicchio, M. (2018). In Proceedings of the 15th International Design Conference (DESIGN 2018). Dubrovnik, Croatia (pp. 917-928).

2. ***Modularisation for Construction: A Data Driven Strategy***.
   Wee, T.P.Y., and Aurisicchio, M. (2018). DS 91: Proceedings of NordDesign 2018, Linköping, Sweden, 14th–17th August 2018.

3. ***Evaluating Modularisation Tools in Construction***.
   Wee, T.P.Y., Aurisicchio, M. and Starzyk, I., (2017). Proceedings of the 34rd ISARC International Symposium on Automation and Robotics in Construction, Vol. 34, Taipei, Taiwan, IAARC, pp. 325-332**.**

4. ***The Application of Quality Functional Deployment to Modular Off-site Construction Products*****.**
   Wee, T.P.Y., Aurisicchio, M., and Starzyk, I. (2017). In DS 87-4 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 4: Design Methods and Tools, Vancouver, Canada.

5. ***A Systems Engineering Framework for Mass Customization in Construction*****.**
   Wee, T.P.Y. and Aurisicchio, M. (2017). In MCPC World Mass Customization and Personalization Conference, Aachen, Germany.

List of Definitions

The terminology used in this thesis can be grouped into industry specific terms, research concepts, and technical terms.

(i) Definition of industry specific terms

Figures 1 and 2 illustrate how various relevant industry specific terminologies are related.

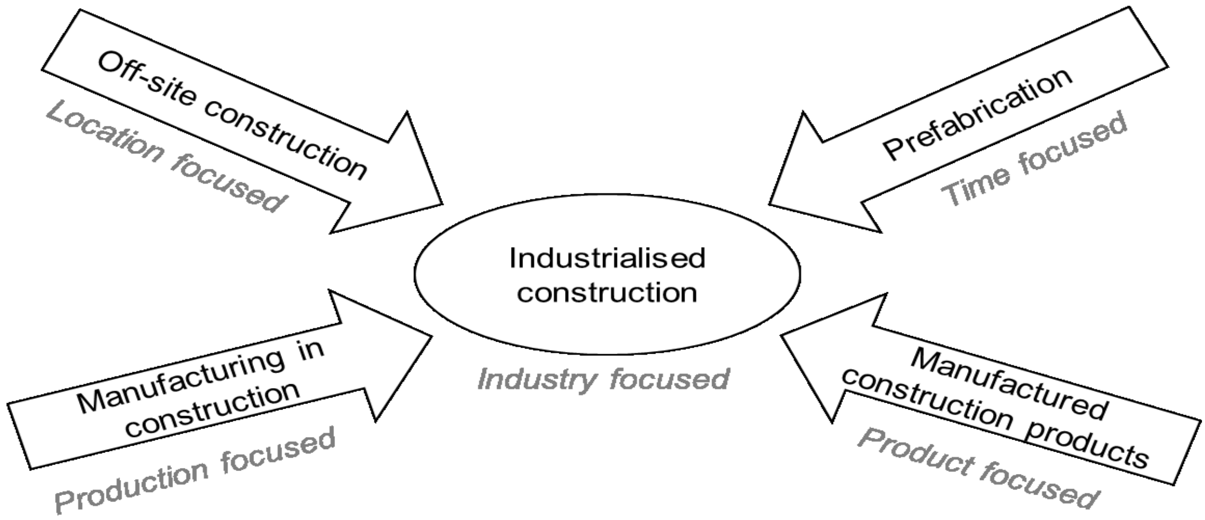


Figure 1. Terminology related to industrialised construction

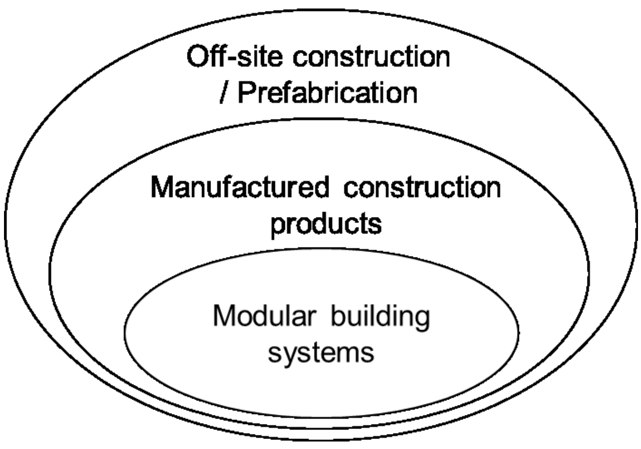


Figure 2. Terminology related to manufactured product in construction

Bespoke construction: Construction projects which are made for a specific customer, typically in relation to traditional on-site construction operations and practices.

Off-site construction: The production of building components or assemblies at a location different to the building site. It involves prefabrication and off-site factories.

Prefabrication: Prefabrication is the production and assembly of building components in a factory or manufacturing site, which are then transported for assembling at the construction site.

Engineered-to-order: A type of manufacturing process in which a product is designed, engineered and finished after an order has been received. The product is engineered to meet the specifications desired by the client or as stipulated in a receive order.

Industrialised construction: A construction system that uses innovative techniques and building components or assemblies manufactured in a factory. They are then transported to the final location and subsequently assembled there.

Manufactured construction product: A building segment or construction product that are manufactured in a factory and transported to the final location for assembling.

Modular building systems: Building systems which have been deconstructed into independent units called modules, to manage the system's complexity or to increase its flexibility.

(ii) Definition of research concept terms

Figure 3 illustrates how various relevant research concept terms are related. This thesis focuses on work at the intersection between systems engineering, requirements analysis, product planning and modularisation.

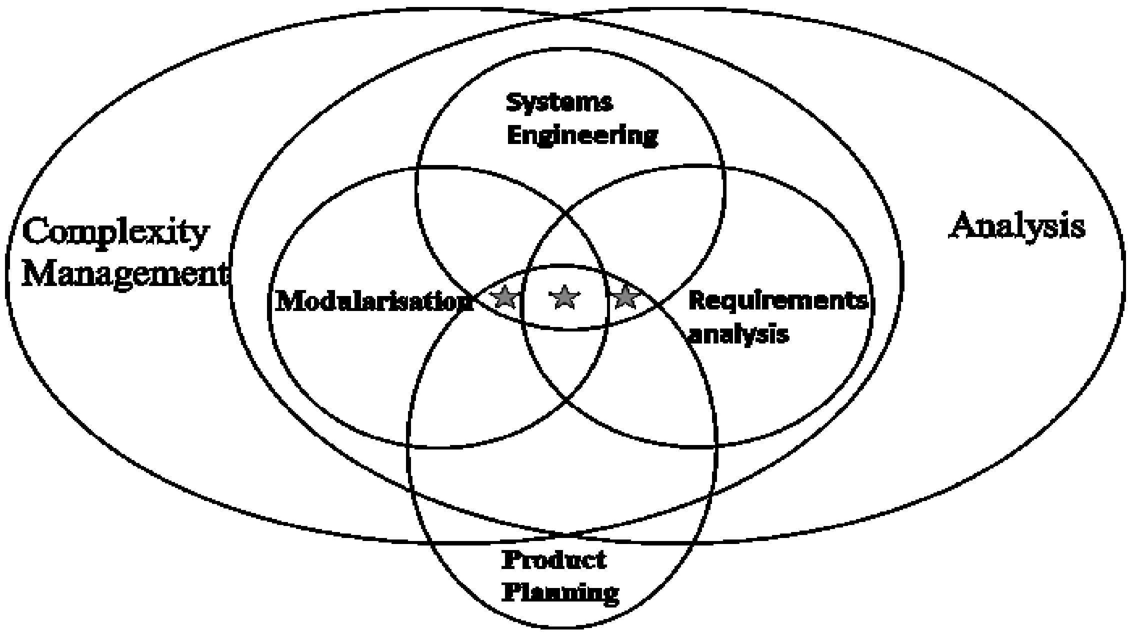


Figure 3. Key research concept terms and their intersection

Complexity management: The management of complex issues which could arise from various sources through the implementation of management or engineering methods. Complexity challenges could arise from business processes along the value chain, design of complex products, decision making to determine an effective product option, or control on patterns of relationships among the system's elements.

Product planning: Product planning is the process of developing a product idea to fulfil a business objective. Product planning may include management of product features, implementation of marketing strategies, and design preparation for product improvement.

Systems engineering: "An interdisciplinary approach and means to enable the realisation of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem: operations, performance, test, manufacturing, cost and schedule, training and support, and disposal" (INCOSE 2019).

Requirements analysis: In systems engineering and software engineering, requirements analysis encompasses those tasks that go into determining the needs or conditions demanded by a new or altered product or project.

Modularisation: The clustering of different product sub-systems or components into modules to increase the flexibility of the overall product system and to support complexity management. Modularisation is an approach that effectively organises complex designs or processes by decomposing them into simpler portions.

(iii) Technical terms used

Approach: An overview or perspective for addressing a problem to attain a desired solution. For example an approach to designing a product is to efficiently meet a customer's requirements, whilst another is to balance multiple business needs (e.g. manufacturing and marketing).

Tool: A device or instrument used to carry out a specific function. For example, QFD is a tool for requirement analysis and DSM is a tool for complexity management of a system.

Method: An engineering method (i.e. engineering design) is a systematic procedure or approach for addressing a problem to attain a desired solution. A method can apply tools. For example the method for modularisation can be the processes from product information collection to the realisation of a module, and the tool implemented can be DSM for interdependencies clustering.

Framework: A foundation or flexible structure of system or concept to address a problem, which can include tools and an approach.

Model: A representation of a phenomenon or system. This can involve information of a phenomenon or system being structured through a tool or framework. For example, the QFD concept is a requirements analysis tool until it has been filled out with information of a case study (e.g. a plantroom).

List of Abbreviations

AM&MD	advanced manufacturing and modular design
AHP	Analytical Hierarchy Process
CI	Coupling Index
DfV	Design for Variety
DfX	Design for Excellence
DfMA	Design for Manufacturing and Assembly
DRM	Design Research Methodology
DSM	Design Structure Matrix
Fr	Functional requirements
GVI	Generational Variety Index
HQFD	Hierarchical Quality Function Deployment
MEP	Mechanical Electrical Pumping
MFD	Modular Functional Deployment
MIM	Module Identification Matrix
Nfr	Non-functional requirements
Ps	Product systems
QFD	Quality Function Deployment

Table of Contents

Chapter 1

Introduction

1.1. Introduction

In 2015, all United Nations member countries adopted the 17 sustainable development goals with the aim to end poverty, protect the planet and ensure that all people enjoy peace and prosperity by 2030. The construction industry, which employed in the first half of 2019 an estimated 7.2 per cent of the United Kingdom's workforce[1] (Office of National Statistics 2019), can play a role in contributing to realising many of these global goals. They include, among others, from Goal 1 (no poverty), goal 6 (clean water and sanitation), goal 7 (affordable and clean energy), goal 8 (economic growth), goal 9 (industry, innovation and infrastructure), goal 11 (sustainable cities and communities), goal 12 (responsible consumption and production) to goal 13 (climate action) and goal 17 (partnership for the goals). Some examples of specific contributions from the construction industry could include employment generation (goals 1 and 8); building renewable power plants and sustainable infrastructure (goals 7, 9 and 13); building better, faster delivery and affordable homes (goal 11); ensures efficient use of resources and minimise the environmental impact through careful planning (goals 12 and 13); and the industry can be an effective partner together with other stakeholders to contribute to goal 17. Contributing to the SDGs requires strong commitments by the industry and companies. There are also challenges to address such as the need to move away from business-as-usual and to adapt business models to fit the requirements of SDGs.

The construction industry is also facing other challenges. In particular, it has difficulty in meeting housing expectations, and productivity in the industry has also stagnated

[1] "EMP13: Employment by industry", Office of National Statistics, August 2019 (https://www.ons.gov.uk/employmentandlabourmarket/peopleinwork/employmentandemployeetypes/datasets/employmentbyindustryemp13)

(KPMG 2016). It is experiencing a technological challenge in that many construction companies have been slow in using new technology to increase efficiency, including in the production of construction products. The industry is shifting from on-site to off-site environments to increase efficiency and delivery. This shift brings in complex engineering management issues (e.g. associated with off-site manufacturing of construction products) in addition to those already in existence.

In the last decade, the growing demand for sustainable high-value building products together with the need for cost competitiveness and fast delivery are pushing further industrialisation of the industry. Housing and labour shortage, increasing social expectation and strict government sustainability targets are also contributing to the move towards construction industrialisation (Gann 1998; Höök 2006; Lawson et al. 2012; and Marchesi et al. 2013).

Although off-site construction has already spread throughout the industry, the depth of its influence is still limited. This is because small- to medium-size prefabricated components used in construction have little total value compared to the size of the whole industry. For example, the UK Commission for Employment and Skills estimated that in 2013 the total market value for off-site construction was just £6 billion, which accounted for only 7% of the total construction industry (KPMG 2016). Despite the current situation, there is great potential for off-site construction to gain more importance as “70% of all construction projects can be conducted using off-site construction components” (KPMG 2016).

Firms investing in off-site construction systems are targeting not just mass-production but also mass-customisation. They want to develop building systems that can be made more adaptable to changing situations thereby reducing engineering risks, while addressing the needs of customers and providing product variation. To achieve this, firms have to invest more in product planning in the early phases of the construction process. In particular, they need to increase the quality and efficiency of the processes and the flexibility in the production of manufactured construction products.

Their approach to planning at present relies on the use of internal knowledge and expertise, rather than on consolidated and systematic methods, methods for requirements management and modularisation. While the benefits of systematic planning methods are well accepted in other industries, their utilisation in the construction industry has been limited. One reason is that each construction project is unique (Gilbert et al. 2013) and the industry tends to tackle engineering work focusing on solution development rather than problem understanding. Another reason is that past research on requirements management and modularisation in construction has not been tested on advanced and industry-relevant case studies. Past research work did not also look off-site construction. The shift from building on-site to off-site (industrialised construction) manufacturing operation provides a favourable environment for the adoption of product planning methods (Jensen et al. 2014), especially in the early stages of the construction process (Veenstra et al. 2006; and Marchesi et al. 2014).

In light of the above background and context, the construction industry needs effective product planning tools to help increase production efficiency, delivery and productivity. This chapter provides an overview of the evolution of the construction technology and explains the research objective. The chapter also discusses the research plans and approaches, and presents the layout of the thesis.

1.2. Overview of development of construction technology

As a result of pressing economic considerations such as cost reduction and increased efficiency, industries continue to change or adapt to the changing environment. Technological development also contributes to the change as it affects industries, production processes and the manner in which goods and services are delivered. It is important to understand the nature of the technological change (e.g. new methods of production) and how such change can influence the development of industries and businesses. In this regard, there is no exception for the construction industry, which is also moving further along the industrial evolution path.

At different stages in the development of the construction industry different technologies have been used. As the industry advances towards a state of mass-customisation, understanding technological influence on industrial shifts in construction, product technical solutions, and requirements for mass-customisation is important to advance the industry.

1.2.1. Technological influence on industrial shifts in construction

The evolution of the construction industry can be characterised by three main dimensions, namely its states, product technical solutions and the production orientation. The principal states are engineered to order, mass production and mass customisation. The main product technical solutions emerged over time are bespoke (Kamara et al. 1999; and Piroozfar and Farr 2013), component, panelar, volumetric (Lawson et al. 2012; and Piroozfar and Farr 2013), platform (Gilbert et al. 2014; and Marchesi and Matt 2017), modular, and parametric (Gunawardena et al. 2013; Gilbert et al. 2014; and Marchesi and Matt 2017). The production orientations are off-site and on-site. Figure 1.1 illustrates progressive shifts in the industry at the intersection of the three dimensions. . As the industry moves from engineered to order towards mass-customisation, the technical solution becomes more complex moving from bespoke to parametric.

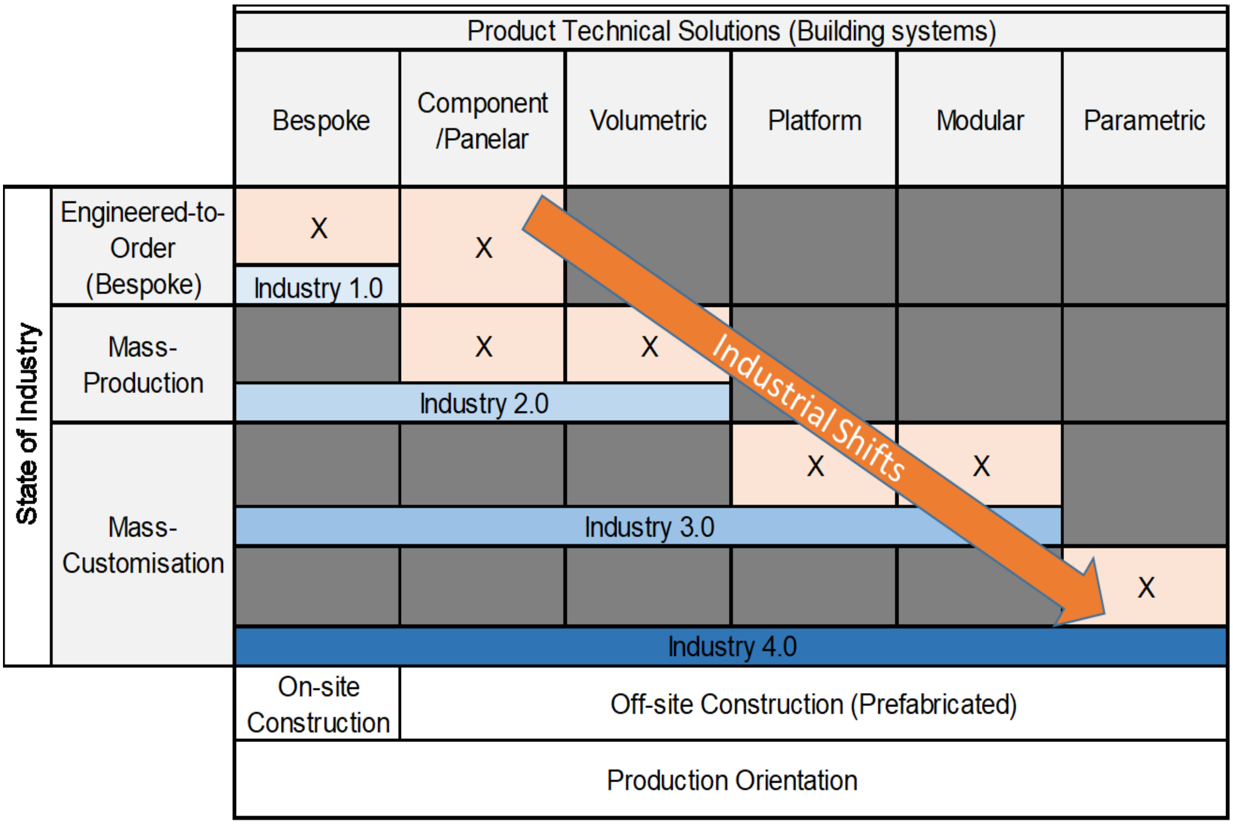


Figure 1.1. Evolution of technology in the construction industry

The three states of industry development are explained below. Note that the mass customisation state has been broken into two sub states to highlight important differences in it.

- **Engineered-to-order (bespoke)** refers to construction projects that are developed to meet a specific client order. Typically, this refers to traditional methods of on-site construction that are labour intensive. It includes some forms of prefabricated components (e.g. bricks, doors, windows).
- **Mass-production** involves increasing use of machine assisted manufacturing and increasing complexity of products manufactured in a factory. Mass-production includes construction operation involving an off-site manufacturing environment.
- **Mass-customisation (1)** relates to the ability to deliver a tailored product and high production efficiencies, which will require more advanced product and production solutions. The technical solution for mass-customisation includes platform and modular product designs. These technical solutions will require the introduction of a fully integrated and digitalised information system (associated with Industry 3.0), as well as semi flexible or restricted production systems.

  The phenomenon of increasing customer demand and industrial shifts is not unique to construction. Many industries including construction are facing the rise in demand for product specifications and for a variety of products. Such situation put a strain on producers to deliver timely, efficiently and cost effectively for customers. Due to the availability of new technologies (e.g. robotics, information systems, data science), advanced solutions can now be developed to address these challenges and help move construction towards achieving efficiency leading to mass-customisation (Cuperus 2003; and Marchesi and Matt 2017).
- **Mass-customisation (2)** relates to the industrial shift that involves product progression, introduction of parametric design and fully flexible production systems. This state of mass-customisation is unique to industry 4.0, which enables completely unrestricted product flexibility and delivery systems (Sun et al. 2017).

1.2.2. Product technical solutions in construction

Among construction companies there are diversities in the use of technical solutions for building systems (Kamara et al. 2013; and Piroozfar and Farr 2013). While there is a shift in usage from simple to more complex approaches, many construction companies have not moved beyond volumetric construction solutions (Lawson et al. 2012; and Piroozfar and Farr 2013). The state of technical advancement in construction has saturated at volumetric design and other more advanced technical solutions (e.g. platform, modular and parametric) have yet to gain more attention in the industry. This contrasts with industries such as the automotive, aeronautics and consumer electronics, which are using platform and modular designs to increase production efficiency and faster delivery of products. The construction industry would need to make an improvement in the development and use of more advanced technical solution designs such as in the areas of platform, modular and parametric to realise mass-customisation.

1.3. Complexities of manufactured construction products

As the technological capabilities of the construction industry continue to develop, the organisation and operations of the industry will increase in complexity. Advancement in technology (e.g. product technical capabilities and production capabilities) will introduce new technological features and requirements, leading to increased complexity. Hence, it becomes increasingly crucial that the new level of complexity be effectively managed to prevent undesired outcome (e.g. wasted time, effort and loss of resources) and to ensure a higher level of industrial efficiency (Gann 1996; KPMG 2016; Marchessi 2016; Sun et al. 2017 and Li et al. 2018).

Complexity management can support implementation of methods for the management and analysis of complex issues, which could arise from various sources. For instance, complexity challenges could arise from business processes along the value chain, design of complex products, decision making to determine effective product options, control on patterns of relationships among the system’s elements, and complex engineering management challenges and trade-offs.

Systems engineering techniques have been used to aid in the management of complex projects such as aeronautics design, robotics, software, and bridge building. Examples of these techniques include unified modeling language (UML), quality function deployment (QFD), and the Vee model. These techniques can offer effective approaches for the management of complex systems. Systems engineering uses a host of tools that include modeling and simulation, requirements analysis and scheduling to manage complexity considerations. It requires an interdisciplinary approach to engineering and engineering management that focuses on how to design and manage complex systems over their life cycles. Construction practices often lack the implementation of such systematic tools. Gann (1996) and Marchessi (2016) argued that the industry could benefit from adopting some of these tools for complexity management.

1.4. Product planning in construction

Effective product planning for manufactured construction products is needed to increase efficiency, reduce the risks of redesign and minimise wastage. To enable further industrialisation of the sector there is a need to acquire more capabilities in advanced manufacturing (Höök 2006; and Marchesi et al. 2013) and firms have to invest more in product planning in the early phases of the construction process. In developing product planning methods, there is a need to define flexible and efficient product and production systems that are adaptable to rapidly changing requirements condition imposed by clients, technological development, business considerations and other corporate reasons. Rigorous product planning, especially requirements management, is key to prevent logic holes and lost resources. Such planning exercise can also contribute to management of product variations and identification of pathways to achieve engineering targets (Wee et al. 2017a).

Modularisation is increasingly being applied in construction to handle product variations and manage product complexity issues (KPMG 2016; and Wee et al. 2017b). Modularisation allows clustering of different product sub-systems or components into modules to increase flexibility of the overall product system and to manage complexity (Borjesson and Hölttä-Otto 2014). It is useful for handling product variations and reducing redesign work (Simpson et al. 2012). Modularisation enables quicker and easier reconfiguration of products to meet customised demands without massive alterations of the product or production operation.

1.5. Research aim and objectives

The aim of this research is to develop product planning methods for complexity management of manufactured construction products. In realising the aim, the research examines systems engineering analysis tools that can be effective for requirements management and modularisation of manufactured construction products. In order to address the research aim, the following objectives were established:

Objective A: Determine research gaps in product planning methods for the development of manufactured construction products.

Objective B: Determine the current design and product development approaches used by of the collaborating company.

Objective C: Develop a framework for efficient, systematic and flexible design of building systems.

Objective D: Develop and evaluate the application of QFD as a requirements analysis tool for manufactured construction products.

Objective E: Develop a method to manage requirements of a complex manufactured construction product.

Objective F: Evaluate current methods to support development of efficient modular construction products.

Objective G: Develop a modularisation approach that addresses multiple modularisation drivers in construction.

This research takes a systems engineering and analytical centric approach to product planning.

1.6. Research plan and approach

Five studies with specific research approaches were undertaken to answer the research objectives. Blessing and Chakrabarti's (2002) "design research methodology" was utilised to guide in the collection and validation of data in this research (Chapter 3). Table 1.1 provides an overview of these studies and their corresponding purposes in relation to the research objective. The table also summarises results of the respective studies and indicates the chapters of the thesis in which the results are to be discussed.

The first study was undertaken to develop a product planning framework through observation and prescription methods (i.e. Study 1 in Chapter 4).

The next two studies were undertaken to investigate requirements management for manufactured construction products. The second study was carried out to establish a requirements management method for a single product, which involves application of Quality Function Deployment (QFD) tool (i.e. Study 2 covered in Chapter 5). The QFD model was applied to a plantroom, which represents a manufactured construction product. The third study was conducted to establish a requirements management method for complex products (i.e. represented by an entire apartment building), which involves Hierarchical Quality Function Deployment (HQFD) (i.e. Study 3 covered in Chapter 6).

The following two studies were undertaken to determine effective modularisation of manufactured construction products. The modularisation research was applied to a plantroom case study. The fourth study evaluates the applicability of existing modularisations tools to address complexity management issues (e.g. product redesign risk, and product technical solutions challenge) in manufacturing of construction products (i.e. Study 4 covered in Chapter 7). The modularisation result was compared against the collaborating company's reference model and fifteen modularisation drivers. The fifth study establishes a multi-driver modularisation approach to produce more effective product solutions (i.e. Study 5 covered in Chapter 7).

Table 1.1. Research methods, studies and summary results

Study	Study objective	Research method	Result	Chapter in thesis
Literature review	Determine research gaps in product planning methods for the development of manufactured construction products.	Desk research, library and literature review	Literature gaps were determined. There is a need for the development of systematic methods for the development of manufacture construction products.	2
Study 1: Examination of product design approach and development of a framework	Determine the current design and product development approaches used by of the collaborating company.	Observation, enquiry and interviews	An understanding of the construction design procedure and product configurator environment, which led to an understanding of requirements needed to develop a framework.	4
	Develop a framework for efficient, systematic and flexible design of building systems.	Observation, enquiry, interviews and prescription	A framework was developed. Components of the framework were validated and evaluated by engineers of the collaborating company.	
Study 2: Requirements modelling with Quality Function Deployment (QFD)	Develop and evaluate the application of QFD as a requirements analysis tool for manufactured construction products.	Reverse engineering, examination of documents, interviews, workshops, validation	A QFD model was developed and evaluated as a requirements analysis tool for manufactured construction products. The QFD model supports a holistic, systematic and structured approach to requirements analysis.	5
Study 3: Requirements modelling with Hierarchical Quality Function Deployment (HQFD)	Develop a method to manage requirements of a complex manufactured construction product.	Reverse engineering, examination of documents, interviews, workshops, validation	A HQFD model was developed, which consisted of a series of QFD models that cover different segments of a modular apartment building. The model also supports further requirements analysis through analysing systems structure, traceability and data analytic solutions of complex building systems.	6
Study 4: Evaluation of modularisation tools	Evaluate current methods to support development of efficient modular construction products.	Application of modularisation tools and approaches	Dependency structure matrixes, modular identification matrix and generational variance indexes were evaluated as modularisation tools.	7
Study 5: Multi-driver modularisation approach	Develop a modularisation approach to address multiple modularisation drivers in construction.	Application of modularisation tools and approaches	An approach for addressing multiple modularisation drivers in construction was developed utilising DSM and index tools (e.g. GVI and coupling index).	7

1.7. Industrial sponsor

This research was undertaken in collaboration with Laing O'Rourke, a major engineering and construction multinational corporation, headquartered in the United Kingdom. The company plans to expand its construction capability through introducing efficient design techniques and product development processes. This is evident by the company's plan to develop a new "advanced manufacturing facility" to accommodate future advancement in building construction technology. In order to fully realise this technological progression, the company is exploring more systematic approaches to modular building system design. In particular, the company is addressing effective design process strategies, product standardisation and product configuration.

1.8. Thesis outline

Following from the Introduction, Chapter 2 provides the literature review and Chapter 3 explains the methodologies employed for the overall research, including approaches undertaken to examine and validate the various systems engineering tools and models. Chapter 4 describes the product development environment at the collaborating company and proposes a framework for complexity management of construction products. Chapter 5 examines requirements management models, which involves the application of QFD tools and highlights the need for systematic product planning tools. Chapter 6 builds on the preceding chapter that addresses requirements management for a single product. The chapter discusses requirements management that involves multi-dimensional and multi-level environment (i.e. a composite of products that made up of the entire building). The chapter explains the application of a HQFD model. Chapter 7 determines a multi-driver modularisation approach for a manufactured construction product. Chapter 8 discusses the findings and contributions to knowledge of this research. It also suggests areas for future research on modularisation strategy for construction. An overview of the outline and structure of the thesis are presented in Figure 1.2. This research has led to the publication of four peer reviewed full conference papers (Wee et al. 2017a; Wee et al. 2017b; Wee and Aurisicchio 2018a; and Wee and Aurisicchio 2018b).

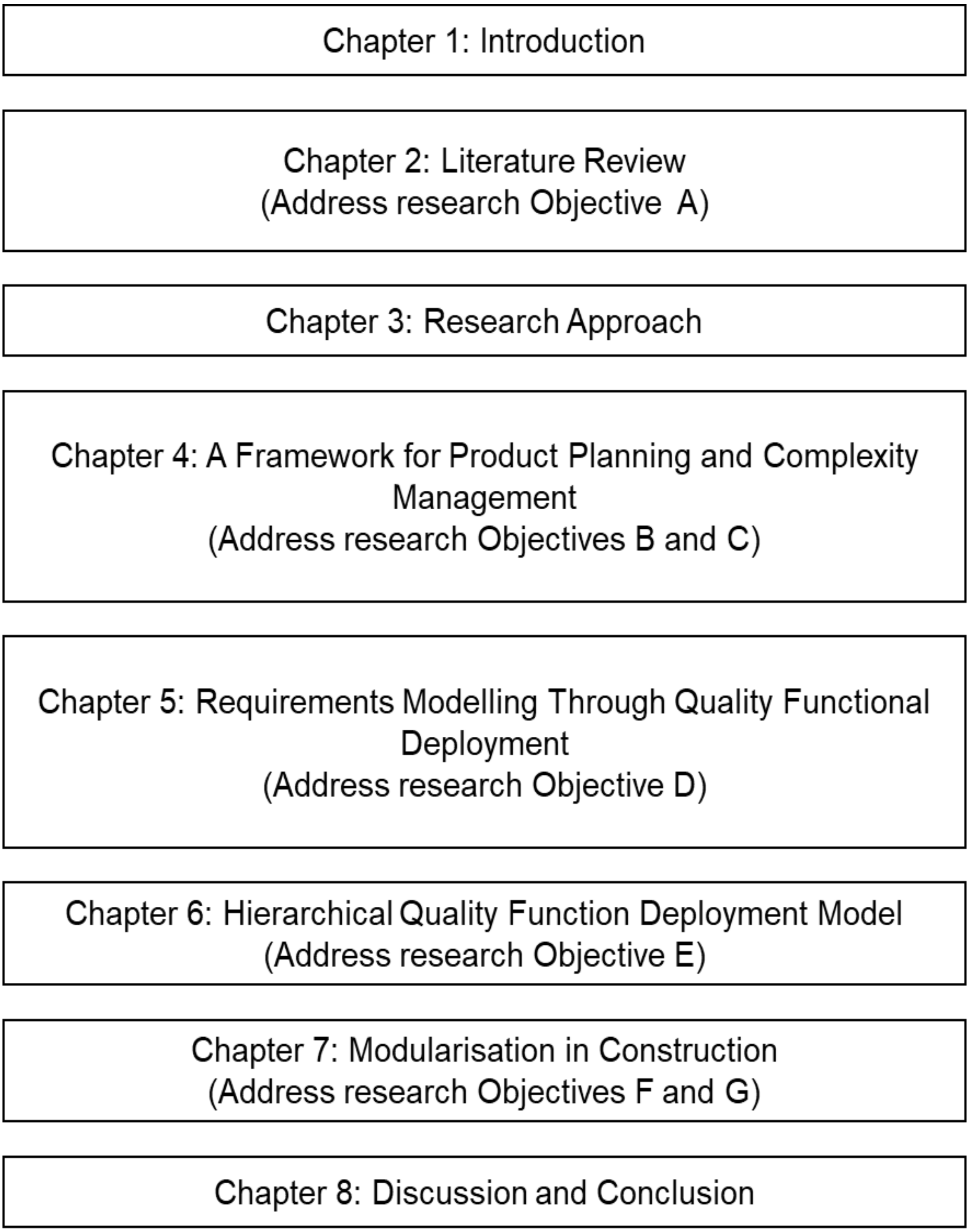


Figure 1.2: Thesis structure and chapters

Chapter 2

Literature Review

2.1. Introduction

This chapter reviews literature that examined tools relevant to product planning and for the development of manufactured construction products. It also covers literature on manufacturing in construction, especially on prefabrication, requirements management, and modularisation.

The chapter is organised into six key sections. Section 1 examines the development of off-site construction and manufacturing in construction. Section 2 analyses literature on product planning frameworks for modular products. Sections 3 and 4 review the application of tools for requirements management and particularly in the construction industry. Sections 5 and 6 review studies that applied modularisation tools and particularly in the construction industry.

2.2. Manufacturing in construction and product development

Increased industrialisation in construction often presents itself as advancement in production capabilities including manufacturing operations and product developments. They usually relate to prefabrication and off-site construction. This section provides an overview of studies relating to prefabrication and manufacturing in construction. It also provides an introduction to the concept of product development, requirements management and modularisation issues.

2.2.1. Prefabrication

Prefabrication refers to production of building components at a location other than the building site. It covers a large scope of products from processed material to panellised system through to modular context. Prefabricated products may include bricks, doors, wall panels, floor panels, room-sized products, and even entire buildings. Prefabrication can generate benefits associated with economies of scale through mass-production (Roger-Bruno 2005; Höök 2006; Emmatty and Sarmah 2012; and Li et al. 2018). Other benefits of prefabrication include:

i. Shorter construction time due to the application of modern manufacturing technologies, automation and levels of standardisation;
ii. Reduce site disruption as a result of a factory-controlled environment;
iii. Better quality control of final products; and
iv. Financial savings by better controlling time and materials, as well as better product techniques.

There is a large spectrum of literature that examined increased industrial or manufacturing in construction. They tend to focus on production techniques, operations, trends and product development. These studies also tend to typically address specific prefabricated components such as panelled, volumetric builds, and mechanical and electrical plumbing. Some of these studies include value chain management (Vrijhoef and Koskela 2000; Arbulu et al. 2003; Court et al. 2006; and Björnfot and Stehn 2007), lean manufacturing (Pasquire and Connolly 2002; Court et al. 2006; and Court et al. 2009), agile production (Court et al. 2006 and 2009), and organisation management (Gann and Salter 2000; Saurin et al. 2008; Dave and Koskela 2009; and Skibniewski and Ghosh 2009). There is a general agreement in the literature supporting the increasing importance of manufacturing in construction to achieve economies of scale and other product advantages. Many studies recommended that important lessons can also be learnt from the experience of other disciplines with application to be adapted for construction (Gann 1996; Lawson et al. 2012; Piroozfar and Farr 2013; and Li et al. 2018). There are also other studies that have attempted to address complexity management but most of them only addressed construction organisation, operation and production methods. There is also agreement in the literature that to enable further industrialisation of the sector, through off-site construction, there is a need to acquire more capabilities in advanced manufacturing and product planning (Höök 2006; Marchesi et al. 2013; and Kasperzyk 2017).

2.2.2. Modular building systems

Modular building systems (MBS) in construction has been utilised within the construction industry for lower quality builds (e.g. timber housing or temporary housing). The concept has been frequently used in many other industries (Gann 1996; and Lawson et al. 2012). The application of MBS for the development of high quality permanent structures is an area that is in its infancy. Its application is expected to facilitate significant technical advancement in design engineering for the construction industry.

A modular construction system can bring several important benefits as compared to the use of traditional bespoke method. Some of these benefits include systems flexibility, risk management, complexity management and lower cost of redesign (Martin and Ishii 2002; and Simpson et al. 2006; and Sharafi et al. 2018). These benefits are associated with the use of prefabrication technology that can support manufacturing of large quantities of volumetric building units under a stable factory-controlled environment, which is not affected for example by weather. Modular systems research is covered in many fields such as in architecture, project management, industry networks, lean production, building configuration and sustainability, structural analysis, steel frames development, design operations, and information management system.

Although MBS can bring about potential advances in manufacturing and mass-customisation, construction projects today utilise high degrees of standardisation. This makes for buildings with high levels of architecture repetition desirable to implement modular building systems (e.g. development of student accommodation, apartment and hospital buildings) (Craig et al. 2000; Lawson et al. 2012; and Gunawardena et al. 2013; and Sharafi et al. 2018).

2.2.3. Product development and product planning

Product development has an important influence on the efficiency, quality and outcome of building projects (Formoso et al. 2002). Many techniques and methods for product development and design processes do exist, but most of them originate from studies made in the manufacturing industry. Product development is the process in which a product is conceived, designed and launched in the market and also includes feedbacks from both production and product use (Ulrich and Eppinger 1995). This involves the identification of customer requirements, concept development, product design, market launch, and evaluation of feedback (Holmes and Yazdani 1999; and Cooper 2000). Ulrich and Eppinger (1995) recommend the use of product development methods because they make the decision-making process and rationale explicit.

Product development also involves product planning which is the ongoing process of identifying and articulating requirements that define a product. Product planning is the process of developing a product idea through till the product is introduced to the market (Simpson et al. 2006; and Soota, T. 2016). Product planning may include management of product features throughout its life, implementation of marketing strategies, and design preparation for product improvement. Product analysis can involve examining product features, costs and quality. It can be used as part of product design to convert a high-level product description into project deliverables and requirements. Techniques for product planning and analysis can include systems engineering, functional analysis, value engineering, and product breakdown (Simpson et al. 2006; Soota 2016; and Bacciotti et al. 2016).

The complexity of building and construction projects can arise from growing business competition in the industry and from increasing demand for higher product development performance. Increasing demand for product quality, shortened lead time and product flexibility have become important competitive aspects in the construction industry (Formoso et al. 2002; and Li et al 2019). Traditionally, construction building design have a high level of associated challenges and complexity. These challenges include conflicting or incomplete requirements, the need to manage trade-offs, the existence of large number of collaborators, and frequent product changes and variations. There is a general agreement for product development to be better planned, more systematic and more effectively controlled to aid the management of complexity. With the advancement of prefabrication and tools that support manufacturing in construction, there is a need to address new level of challenges and complexity. Product development plays an important role for the development of manufactured construction products to meet increasing product requirements in construction. The lack of design planning and control increases the possibility of poor coordination between project collaborators, poor project documentations, wasted resources, and the overall lack of information to complete production tasks (Koskela et al. 1997; and Kamara and Anumba 2001).

The literature concurs that buildings and construction projects are increasingly becoming more complex. The demand for product development has also become increasingly more challenging and product development needs to be more sophisticated to match new level of complexity (Gann 1996; Jensen et al. 2014; Marchesi et al. 2015; and KPMG 2016). This shows that product development technology has become increasingly more important and valuable for construction. Therefore, there is a need to develop more systematic analysis tools for construction (Jensen et al. 2014; Marchesi et al. 2015; and Sharafi et al. 2018).

Historically very few systematic tools have been applied in construction. In cases when they do, their application tend to focus on improving engineering processes as opposed to product systems (Formoso et al. 2002; Liu and Wang 2011; and Lee et al. 2017). This is often attributed to the limited readiness of the industry to adopt systematic tools. As the construction industry advances and becomes more in line with a manufacturing process, increasing opportunities are emerging for the adoption of systematic product planning tools (Gann 1996; Jensen et al. 2014; Marchesi et al. 2015; and KPMG 2016). Some examples of these tools in construction include those that examined design processes and Design for X (DfX) (Pasquire and Connolly 2003; and Todic et al. 2012). DfX is a concept for designing multiple sets of variables or values including Design for Manufacturing and Assembly (DfMA).

Modularisation in product planning can be used to develop product modules which could contribute to increased product flexibility. It has been considered as a strategy for dealing with building modules development (Veenstra et al. 2006; Gilbert III et al. 2013; and Jensen et al. 2014) and can be used for complexity management in product development. It is often linked with other product development aspects such as requirements management, which is an important aspect of product planning.

2.2.4. Requirements management

Requirements management is the collaborative and iterative process to identify all stakeholders, and elicit, document, analyse and validate requirements (Fernandes et al. 2015). The requirements management process has been studied both in the fields of engineering design and systems engineering. In the former, the process of establishing design requirements, typically referred to as problem definition, is recognised as one of the most important steps of designing (Haik et al. 2010; and Aurisicchio et al. 2013). In the latter, the focus is on how to manage the requirements of complex systems over their life-cycles (Zimina and Pasquire 2010; and Kossiakoff et al. 2011). Over time various tools have emerged to manage requirements. These include, for example, product design specification documents, Quality Function Deployment (QFD), UML and SysML (Burge 2004; Dai et al. 2012; Soota, T. 2016; and Bacciotti et al. 2016). These tools typically represent requirements information using lists, trees, networks and matrixes (Kossiakoff et al. 2011; and Aurisicchio et al. 2013).

2.2.5. Modularisation

Modularisation is often referred to as the clustering of product sub-systems for the formation of a module or a product subsection. Modularisation is an approach that effectively organises complex designs or processes by decomposing them into simpler portions (Jose and Tollenaere 2005; Borjesson 2010; and Sharafi et al. 2018). A modular system is one that consists of a number of assemblies or modules, which are self-contained with well-defined interphase (Piroozfar and Farr 2013). Modularisation is useful to support design for variety (DFV), design strategies in manufacturing and mass-customisation (Kreng and Lee 2004; Jose and Tollenaere 2005; Piroozfar and Farr 2013; and Sharafi et al. 2018). Mass-customisation aims at meeting the demands of individual customers by facilitating high product variety with near mass-production efficiency. To realise mass-customisation, manufacturers tend to implement more efficient and flexible product designs and manufacturing strategies (Kohlhase and Birkhofer 1996; Kreng and Lee 2004; and Suh et al. 2007). Modularisation can support mass-customisation through the development of modules that can be quickly assembled to produce a spectrum of differentiated products (Erixon 1996; Kohlhase and Birhofer 1996; Jenson et al. 2015; and Marchesi and Matt 2017). It also allows for modules to be assembled outside of the main assembly line and then for those modules to be brought onto the main assembly line for the final product assembly (Piroozfar and Farr 2013).

The potential benefits of modular construction systems have been well documented in the literature. These benefits (e.g. product flexibility, risk management, and complexity management) are associated with the use of prefabrication technology that can support manufacturing of large quantities of building components under a stable factory-controlled environment. These benefits are related to increased production efficiencies and shortened project life-cycles (Lawson et al. 2012; and You and Smith 2016). This is a result of the combined application of modern manufacturing technologies, automation and standardization. In addition, modularisation supports the reduction of product design risk and minimises the potential impacts associated with future changes in business requirements (Koh et al. 2016). If a product is highly modularised, it is easy to be assembled, disassembled and recycled (You and Smith 2016).

Modularisation drivers can be thought of as modularisation forces, specific to a company's strategy. Modularisation drivers allow, for example, for the satisfactory achievement of production goals (Erixon 1996; and Borjesson 2010). Past research has identified twelve modularisation drivers, namely *technical specification*, *styling*, *carry over*, *product planning*, *technology push*, *production/organisation*, *common unit*, *separate testing*, *purchasing*, *maintenance*, *product upgrading* and *recycling* (Erixon 1996; and Borjesson 2010). It is noteworthy that among these drivers some target concentration of product or operational dependencies. This involves grouping together components that are naturally more closely associated with one another. For example, technical specification aims at clustering together components based on their functionality and component dependency. Similarly, manufacturing takes an operational or process perspective. Other drivers are strategic and aim at achieving business objectives. One example is the common unit modularisation driver, which acts as a method for standardising the sections of the product and developing a platform. It can reduce redesign costs and increase business stability.

2.3. Product planning frameworks for modular products

There are many frameworks outside of construction that have been developed to support product planning (Borjesson 2010). A subset of them is centred on modular product planning using techniques for requirement management, product architecture definition and modularisation (see Table 2.1). These frameworks often involve the application of QFD combined with a modularisation tool (Borjesson 2010). The modularisation tools include Design Structure Matrix (DSM) (Ulrich and Eppinger 2008; and Pezhman et al. 2017), Modularisation Identification Matrix (MIM) (Erixon 1998; and Borjesson 2010), Coupling Index (CI) and Generational Variety Index (GVI) (Martin and Ishii 2002; and Simpson et al. 2006).

Table 2.1. Product planning frameworks

Framework	Data type	Description
Extended implementation structure matrixes (EISM) (Sellgren and Andersson 2005)	QFD 1 (CR-FR); QFD 2 (FR-TS); EISM	Intended to bridge the "hard" technical requirements with "soft" interactive requirements (Borjesson 2010).
Modular Functional Deployment (Erixon 1998)	QFD 1 (CR-PP); QFD 2 (PP-TS); Module identification matrix (modularisation drivers to TS)	CRs are decomposed into controllable PPs. TSs with similar properties are grouped with strategic intent into modules. TSs are grouped by product property and modularisation driver.
Modular product platforms through Generational Variety Index (GVI) and Coupling index (CI) (Martin and Ishii 2002; and Simpson et al. 2006)	QFD 1 (CR-ER); QFD 2 (ER-TS); GVI; CI	QFD 1 and QFD 2 are used to map interdependencies between CRs, ERs and TSs. QFD 2 is used to generate GVI. Coupling matrix is used to generate CI. The components to develop a platform are grouped based on GVI and CI.

Technical solutions = TS; Customer requirements = CR; Functional requirements = FR; Engineering requirements = ER; Product properties = PP.

Modularisation methods have been applied to product planning frameworks in construction. Two major studies in this area were conducted by Veenstra et al. (2006)

and Gilbert III et al. (2014). Both studies combine requirements management (utilisation of QFD tools) with platform design. Veenstra proposed a modularisation method for house building, which focused on the development of product platforms. Requirements management was conducted through the development of QFD matrixes. For platform design, Veenstra (2006) study used GVI together with CI to identify residential house features that could be turned into modules or platforms. Gilbert (2014) study applied QFD together with axiomatic design and product platform design for the development of modules and his earlier study dealt with modularisation of temporary modular buildings (Gilbert III et al. 2013). These modularisation methods are explained in detail in Section 2.6.

2.4. Requirements management tools

There are various requirements analysis tools available. These tools can be categorised into three types: hierarchy-based tools, diagram-based, and table or matrix-based (Kossiakoff et al. 2011; and Aurisicchio et al. 2013).

2.4.1. Hierarchical-based tools

The hierarchy-based tools organise a set of requirements in a tree consisting of parent to children relationships. Hierarchy-based tools support checking and structuring of requirement analysis aspects. Many hierarchy-based tools take the format of a tree structure. Hierarchy-based tools are often used prior to more structured methods for requirements management such as QFD (Crow 2011; and Asadabadi et al. 2017). These tools can help group, check and refine requirements analysis, which helps attain better requirements structuring. Examples of hierarchy-based tools include hierarchical trees, affinity diagrams, and Viewpoint Analysis (VA) (Burge 2011; and Aurisicchio et al. 2013).

2.4.2. Diagram-based tools

The diagram-based tools organise requirements in a network structure consisting of nodes and arcs. Diagram-based tools consist of a distinctive format, which can be used in requirements analysis. An example of a diagram-based tool is the functional flow diagram (FFD), which can be used to check individual functional requirements for necessity and feasibility, and to check a set of requirements for completeness (Robertson and Robertson 1999).

2.4.3. Table or matrix-based tools

The table or matrix-based tools organise requirements into a tabular format. Examples of these tools include Systemic Textual Analysis (STA) and QFDs. STA is a table-based tool that consists of a method and table format (Burge 2004). It facilitates requirement check and structuring. It also facilitates checking of missing requirements in a set through visual inspection of matching functional requirements to non-functional requirements. QFD is a more commonly used requirements analysis tool in a matrix structure (Chan and Wu 2002; Herzwurm and Schockert 2006; and Dai et al. 2012).

2.4.4. Quality Function Deployment

This research focusses on and implements Quality Function Deployment (QFD) as a tool for requirements management. QFD was selected over other tools (e.g. viewpoint analysis and functional flow diagrams) because of it’s systematic, data centric and comprehensiveness advantage as well as it’s compatibility with modularisation tools (see Section 2.3). QFD is a tool to map customer requirements to technical solutions and product components using a system of matrixes. It has been applied to support product development in a variety of industries, ranging from consumer electronics to vehicles and buildings construction (Wasserman 1993; Kahraman et al. 2006; Yeh et al. 2011; Kwong and Bai 2013; Hadidi 2016; and Fargnoli et al. 2018). The QFD tool involves incorporation of multiple perspectives in product development (Cohen 1995; Akao et al. 1997; and Kwong 2003). The first two matrixes of QFD (i.e. QFD1 and QFD2) are typically used to improve the value of product planning activities. The reliance of QFD on quantitative data and its system orientation make it particularly suitable to this objective. QFD is a prominent tool for ensuring product quality and is increasingly used for modular design (Simpson et al. 2012; Borjesson and Hölttä-Otto 2014; and Hadidi 2016).

There has been significant research interest in using QFD to support product design. Many focused on the benefits of applying QFD to analyse product requirements.

These benefits include efficient, structured, comprehensive, strategic and robust analysis of requirements. QFD has the potential for further development in terms of design automation and integration with other tools (Kreng and Lee 2004; and Almannai et al. 2007). For example, research has been undertaken to integrate QFD with the Analytical Hierarchy Process (AHP), Generational Variety Index (GVI), and TRIZ (Yamashina et al. 2002; Kwong and Bai 2003; Hölttä-Otto et al. 2008; and Simpson et al. 2012).

2.5. Requirements management in construction

There are many studies involving requirements management in construction, which ranges from traditional requirements capture and documentation (Kamara et al. 2002; and Kamara 2013), and project management (Pheng and Yeap 2001; and Ahmed et al. 2003) to computer aided information modelling (Singhaputtangkul et al. 2013). However, a large portion of these studies focused on projects management, as construction is regarded as a project orientated industry (Kamara 2013).

Some of these studies on requirements management focus on topics such as evaluation of management and contractors (Juan et al. 2009; and Hadidi 2016), project information management (Baldwin 1998), implementation feasibility of projects (Yang et al. 2003), quality control of projects (Lee et al. 2009), marketing strategies (Dikmen et al. 2005), and cost optimisation (Lim et al. 2015). These studies on requirements management in construction often implement a combination of requirements analysis tools and hierarchy-based tools that then supports application of table-based tools. There are also studies on requirements management in construction (e.g. Kamara et al. 2002, and Kamara 2013). Some of these studies used computer aided tools to process requirements information (Pheng and Yeap 2001; Juan et al. 2009; Lee et al. 2009; Singhaputtangkul et al. 2013; and Prasad et al. 2015).

Traditionally, construction is viewed as project-based with custom built products. Client requirements are a primary source of information for building projects. The capture of building requirements is often not straightforward, as there is a need to capture and translate client and business needs into construction terms (Kamara et al. 2002; and

Kamara 2013). The quality of captured building requirements information can be incomplete, changing, fragmented and not well defined. The capture of client requirements for building is usually accompanied by design process of sketches, drawings and a project brief. While this has resulted in successful projects, they have limitations in that they do not adequately capture requirements in building design (Kamara and Anumba 2001; and Kamara 2013).

Many studies on requirements management are associated with traditional bespoke construction but a limited number of them relates to industrialised construction (off-site construction and manufacturing in construction). Requirements management relating to off-site construction and manufacturing in construction need to take into account additional layers of complexity and requirements (e.g. assembly and production sequencing) arising from manufacturing operations. Further development in requirements management in construction is needed to increase efficiency and facilitate advancement of the industry.

2.5.1. Quality Function Deployment in construction

Most QFD research in construction tends to focus on the application of matrixes or the development of algorithms for design automation (Pheng and Yeap 2001; Juan et al. 2009; Lee et al. 2009; Singhaputtangkul et al. 2013; Prasad et al. 2015; and Fargnoli et al. 2018). QFD applications in construction also tend to follow the traditional implementation approach. This involves use of the QFD1 matrix to translate “customer requirements” into “technical solutions”, and use of the QFD2 matrix to turn “technical solutions” into “product components” (Yang et al. 2003; Dikmen et al. 2005; Wikberg et al. 2011; Lim et al. 2015; and Prasad et al. 2015). In general, existing QFD studies in construction were found to lack organisational rigor and comprehensiveness in the application of the matrixes. Past studies often tend to focus on demonstrating the application of QFD through simple examples (often including a small number of requirements) rather than addressing complex requirements sets. Only a few studies have moved away from the traditional QFD implementation to investigate alternative requirements modelling methods for the construction industry. Veenstra’s application of QFD to house building, which focuses on the development of product platforms through the Generational Variety Index, captures customer requirements in the rows of the QFD matrix and product modules in its columns (Veenstra et al. 2006). In contrast, Gillbert's application of QFD to temporary housing involved mapping customer requirements in the rows of the QFD matrix and non-functional requirements, constraints and functional requirements in its columns (Gillbert III et al. 2014).

In addition, a further set of studies has attempted to implement a broader variety of requirements and a more rigid organisational structure of such requirements. For example, Dikemen's application of QFD categorises different types of customer requirements but it does not cover other stakeholders' requirements (Dikemen et al. 2005). Yang's application of QFD includes "building needs" together with customer requirements as part of a concept to compare decision making in in-situ construction and pre-cast construction (Yang et al. 2003). The study, however, is limited to handling only customer and building needs, which are represented on separate matrixes. Armacost proposed to use the Analytical Hierarchy Process to prioritise customer requirements (Armacost et al. 1994). The study focused on industrialised housing and addressed requirements not covered in other research such as requirements for manufacturing, transportation and maintenance. The study, however, focused solely on customer requirements prioritisation and does not include the whole QFD matrix (Armacost et al. 1994).

2.5.2. Hierarchical analysis in construction

The utilisation of hierarchical analysis (e.g. application of hierarchy-based tools) can be an effective way for requirements management. Hierarchical analysis in requirements management tend to focus on construction project and process, and less on the building as a whole. Specifically, Analytical Hierarchy Process has been applied on assessments of different aspects of construction projects (e.g. suppliers, contractors, and technologies) (Cheung et al. 2001; Dikmen and Birgonul 2006; Cheng and Li 2007; and Wong and Li 2008) and risk management evaluation in construction (Mustafa and Al-bahar 1991) and cost assessment (An et al. 2007). Many of these hierarchical analysis studies in construction also implement QFD or computer aided tools or a combination of both. There is still a lack of implementation or application of these more advanced requirements management methods than existing methods in construction.

An example that combines hierarchical analysis with QFD in construction is the work covered by Hadidi (2016). The study only involved evaluation of engineering design contractors and used several QFD matrixes to capture various aspects (e.g. safety, engineering capabilities, technical competency, product quality and service quality, project management, service and budgeting) in the evaluation of engineering contractors. The study also only examined a single requirements management level and does not consider other project management levels (e.g. the link between executive management design consideration, contractors engineering design evaluation and subcontractors). The study is also limited in that it does not take into consideration the large scale of construction projects (involving different parts of a building) and upstream (executive) consideration in relation to downstream (detailed level) factors.

Studies on hierarchical analysis through product breakdown are covered by Singhaputtangkul et al. (2013) and Singhaputtangkul and Zhao (2016). These studies included product breakdown of a building, which enveloped into external wall then window glazing and then shading devices. The main focus of these studies was on the proposal and development of a software for fuzzy decision making and QFD. In this regard, these studies have limited application in relation to hierarchical analysis.

2.6. Modularisation tools

Modularisation tools have been developed and frequently applied in many industries (Gann 1996; and Lawson et al. 2012). Past research on modularisation have contributed to the development of tools including the *functional flow block diagram* (Emmatty and Saramah 2012), the *dependency structure matrix* (DSM) (Hölttä-Otto 2005; Ulrich and Eppinger 2008; Pezhman et al. 2017; and Shabtai et al. 2017), the *extended implementation structure matrix* (Sellgren and Andersson 2005; and Borjesson 2010), the *modular identification matrix* (MIM) (Erixon 1996), *axiomatic design* (Marchesi 2015), and the *modular product platform* via the *generational* *variance index* (GVI) (Simpson et al. 2012; Jung and Simpson 2016; Jung and Simpson 2018; and Wang et al. 2018). DSM, MIM and the modular product platform are further explained below as they have been receiving more attention than the others. This section reviews the main tools and approaches for modularisation. Acccording to Hölttä-Otto (2005) and Borjesson (2010) there are three main approaches: Heuristics, Design Structure Matrix, and Modular Function Deployment. This section also covers literature explaining modular platform designs.

2.6.1. Heuristics

Heuristic tools can help capture how designers think. They are based on the application of patterns of biased judgments, represent sensible estimation procedures, draw on underlying processes that are highly sophisticated, and are normal intuitive responses (Zamirowski and Otto 1999). Heuristics can also capture the flow of matter, energy, and information between functional elements in a function-structure diagram (Zamirowski and Otto 1999).

An example of heuristics is the functional flow block diagram, which is popular for the development of modular systems (see Figure 2.1; and Hölttä-Otto 2005). Functional flow analysis such as “dominant flow”, “branching flow” and "conversion–transmission" helps segment the overall system and determines which flows should be encapsulated in which modules (Stone et al. 2000). To further develop modular designs, the analysis of modular components such as discrete scalable, reusable modules and well-defined modular interfaces should be pursued. An example of this methodology is described in Emmatty and Sarmah (2012), which illustrates a good level of conceptual and practical results. The study, however, is only applied to a modular watch.

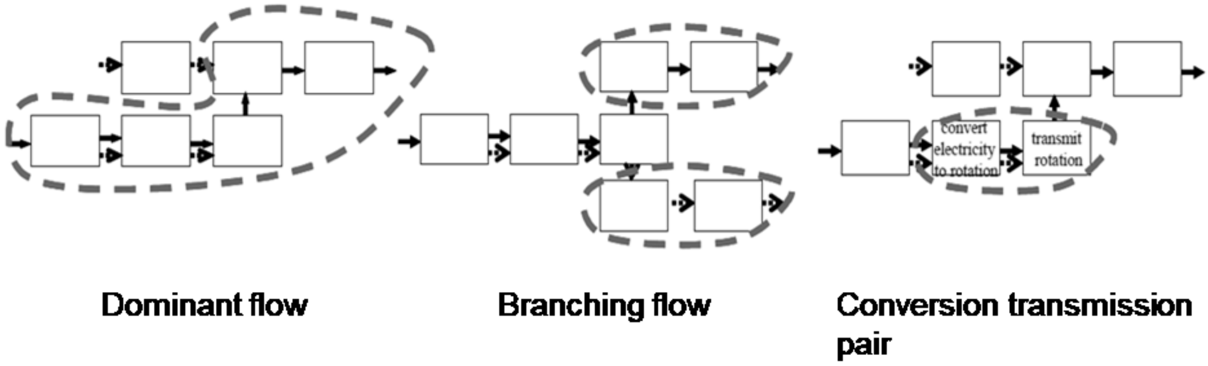


Figure 2.1. Functional flow analysis and function clustering for module development (Source: Hölttä-Otto 2005)

2.6.2. Dependency Structure Matrixes

Dependency Structure Matrixes (DSM) are tools for mapping systems interdependencies represented in a matrix form (see Figure 2.2.). DSM can be used for the analysis of product systems and engineering processes (Hölttä-Otto 2005; Baldwin et al. 2008; Lee et al. 2017; Pezhman et al. 2017; and Kulkarni et al. 2018). It utilises sequencing or clustering algorithms to organise the sub-systems of a system (Choo et al. 2004; and Ulrich and Eppinger 2008). An extensive discussion of the features, operation and relationship of DSM to modularisation is covered in Section 2.7 and Chapter 7.

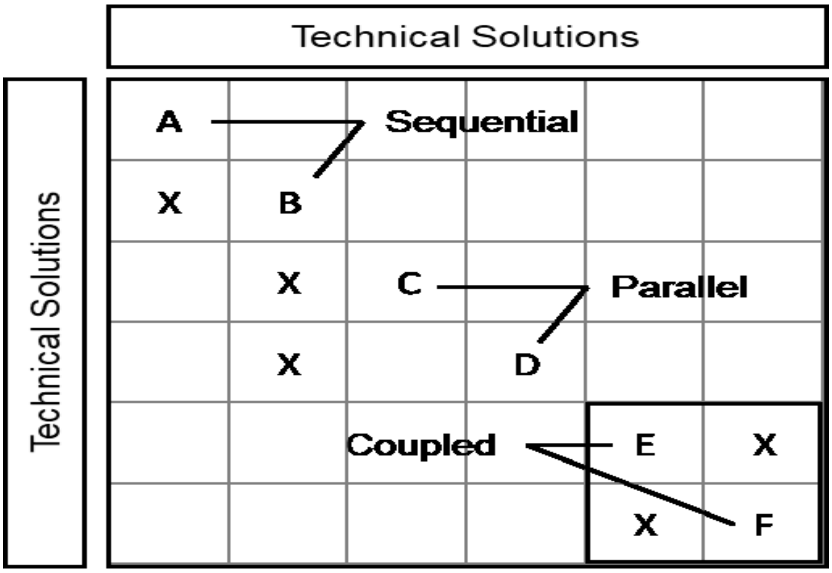


Figure 2.2 Design Structure Matrix (Source: Borjesson 2010)

2.6.3. Modular Functional Deployment

Modular Functional Deployment (MFD) structures customer requirements into specific statements and link them to measurable and controllable product properties, which are then linked to technical solutions (see Figure 2.3; and Erixon 1998). It utilises unique matrix tools referred to as modularisation identification matrix (MIM). An extensive discussion of the features, operation and relationship of MIM to modularisation is covered in Chapter 7.

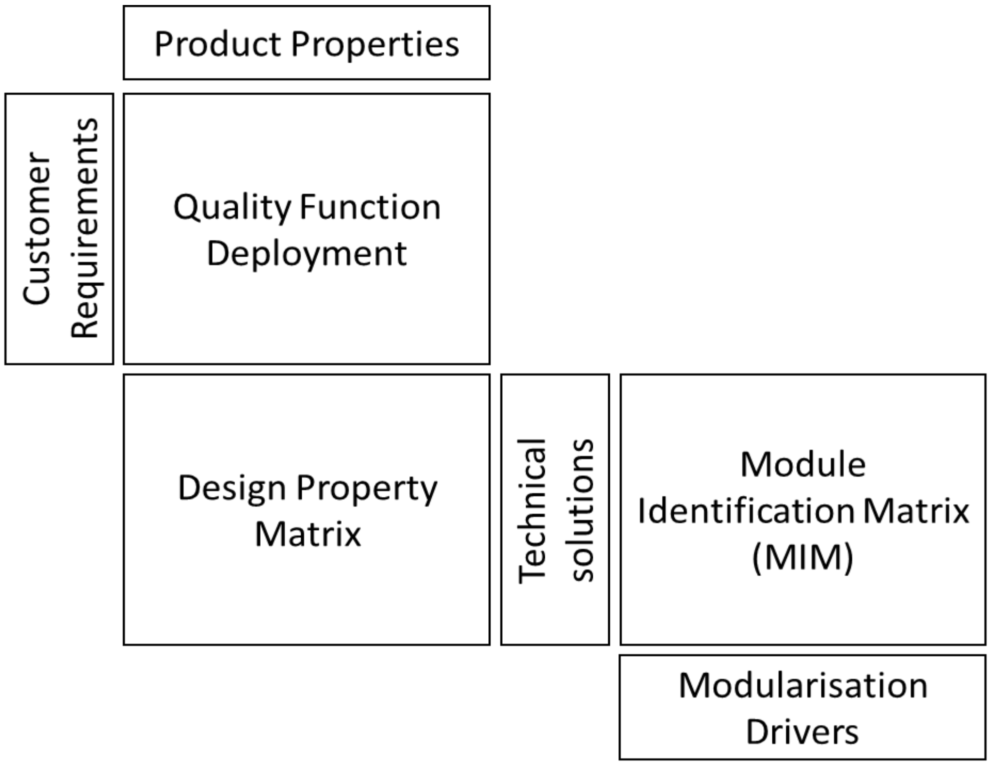


Figure 2.3. Modular Functional Deployment (Source: Borjesson 2010)

MIM is a QFD-like tool that is used to identify which product sub-systems should be clustered into modules (Erixon 1996; and Borjesson 2010). It maps modularisation drivers against product sub-systems and provides a visualisation of the interrelationships between modularisation drivers and product sub-systems. The visualisation supports implementation of modularisation rationale with respect to modularisation drivers (Erixon 1996; and Borjesson 2010).

2.6.4. Modular Platform Designs

The modular product platform is effective at dealing with product design variances and uncertain future product requirements. It consists of clustering common product sub-systems that reoccur across a product family and standardise them into a product platform (Meyer and Lehnerd 1997). It has been successfully adopted in industries such as automotive (Gann 1996) and aeronautics (Simpson 2004). Its application has helped reduce costs associated with product development by using a handful of platforms to create a variety of product families (Cuperus 2003; Simpson 2004; Pan et al. 2008; and Song et al. 2019). In particular, manufacturing and design costs can be reduced as each module has only a few unique features that need to be redesigned each time (Gilbert et al. 2013). As a result, a common platform can relieve flexibility requirement on the production line. A modular platform can be generated, for example, through the utilisation of the generational variety index (GVI) and coupling indexes (CI). GVI supports the identification of product sub-systems, which are less likely to require redesign (Jiao et al. 2007). In particular, GVI indicates the amount of redesign required for future product designs and CI shows how closely two product components are linked together. GVI can be developed through an adapted QFD model, while CI is acquired through the development of a coupling matrix (Martin and Ishii 2002).

2.7. Modularisation in construction

Historically very few modularisation methods or tools have found their way into construction and when they have, their focus has been on improving engineering processes as opposed to product systems (Liu and Wang 2011; and Lee et al. 2017). This is often attributed to the limited readiness of the industry to adopt systematic tools. However, increasing opportunities are emerging for the adoption of these methods as the construction industry advances and becomes more in line with manufacturing process (Gann 1996; Jensen et al. 2014; Marchesi et al. 2015; and KPMG 2016). Within the research undertaken in the construction sector, modularisation has been considered as a strategy for dealing with building modules development (Veenstra et al. 2006; Gilbert III et al. 2013; and Jensen et al. 2014). Two major researches on modularisation relevant to the construction sector were carried out by Veenstra (2006) and Gilbert et al. (2013).

Gilbert et al. (2013) have used axiomatic design and product platform design for the development of modules for temporary modular buildings. The methodology adopted by these researchers suggests that modules can be developed through grouping system’s common functional requirement and physical design parameters. The methodology categorises modules into common and specialist modules. The essential function of buildings is captured by core modules, which basically act as a studio apartment module and additional required features are designated to the specialist modules.

Veenstra (2006) attempted to tackle modularisation and platform issues in the housing industry. The study used GVI together with coupling indexes (CI) to identify residential housing product sub-systems that could be turned into modules or platforms. Veenstra’s study emphasised that GVI and CI together support a better understanding of external design forces. The study follows the decision rules set by Martin and Ishii (2002) to determine modules and platforms. Product sub-system with no or low GVI were turned into fully or partially standardised platforms. Product sub-systems with low *coupling indexes–supply* (CI-S) were considered for higher levels of modularisation. The study approached modularisation and platform design by tackling product uncertainty and risks. It demonstrated the benefits of using GVI and CI as tools for modular platform development in construction.

An example that deals specifically with temporary modular systems is described in Gilbert III et al. (2013). The methodology suggests that modules can be developed through grouping system’s common functional requirement and physical design parameters. The study categorised modules into common modules and specialist modules. The former is applicable to overall systems regardless of requirement variations. The down side of this work is that it only analyses a case study on temporary modular systems and would require further work in order to reach a practical modularisation application. It is also worth considering using sub-modular systems since some building modules can be complex. In addition, the possibility of dividing modules into sub modules may be of interest. For example, mechanical and electrical plumbing can contain a high density of functional requirements and can be considered for further segmentation.

2.8. Discussion

Manufactured construction products have been predominantly studied by researchers in civil engineering, architectural and management contexts. Many of the studies have limitations in examining complexity management and product planning in construction. This is because many of them were developed specifically to explain manufactured construction products (including modular products) from non-product design and non-engineering perspectives.

There is an increasing recognition for the need to provide an integrated approach to explain manufactured construction products based on product systems design with strong emphasis to be given to product development, process, strategies and design coordination (Pasquire and Connolly 2002; and Gunawardena et al. 2012).

In addition, studies that have developed and evaluated systematic methods for product planning including modularisation in construction are also limited. The shortages may be due to construction projects being traditionally bespoke in nature and are less perceptible to the adoption of systematic methods. Where relevant studies exist, they have limitations in that they do not apply the systems engineering approach to address challenges in the design of manufactured construction products (e.g. product efficiency, flexibility and variability).

The studies of Veenstra et al. (2006) and Gillbert III et al. (2014) provided insights into systematic modular and platform design in construction. Both studies show the benefits of applying systematic frameworks and methods for design of modular construction products. However, the two studies have limitations in that they do not consider the full complexity of the requirements management and modularisation problem. In addition, while these studies looked at modularisation, they are limited in the consideration of the wider industrial context. For instance, manufacturing, assembly and business needs were not considered in depth. Further research and development of modularisation tools, based on a systematic approach and specifically for the construction industry, is needed.

There are many frameworks outside of construction that have been developed to support product planning (Borjesson 2010). Most of these frameworks involved application of requirements management (through QFD) that combined with a modularisation tool (e.g. DSM, MIM or platform design). They have proven to be effective at handling complexities in product planning in non-construction industries. In this regard, it is beneficial to learn and adapt from these frameworks for application in construction.

Tools to support the analysis of requirements for modular construction products have to capture a variety of information types including requirements, product systems, the relationships and dependencies between them. Such tools have to facilitate product planning and should be able to integrate or use with other tools (e.g. modularisation tools). Tools with numerical features are preferred as they enable quantitative analysis and justification of strategies. Based on this consideration and given that it can support the design of construction products, the QFD tool is selected for application in this research.

Applications of QFD in construction typically follow the traditional approach, which distinguishes customer requirements from technical solutions. In order to increase the applicability and potential benefits of QFD to the construction industry there is a need to further investigate the QFD concept focusing on non-functional and functional requirements as advocated by systems engineering principles. In particular, a functional approach to QFD is needed to capture a set of complex requirements, which is typical of the construction industry (Burge 2007; and Dai et al. 2012). This would require the investigation of the organisational structure of QFD requirements to integrate various stakeholders' perspectives.

As construction becomes increasingly complex, more advanced requirements management methods are also needed. The utilisation of hierarchical analysis can be an effective way for addressing complexities in requirements management. But hierarchical analysis for construction tend to focus on project or process, and less on the building as a product. The focus of existing studies also tends to be based on non-product perspectives such as evaluation methods of construction contractors or on software development. As a result, the application of hierarchical analysis for complex requirements management is limited.

Further development of effective requirements management for construction products should not examine product requirements at face value but consider requirements breakdown at project or product management levels (e.g. the link between executive management design consideration, contractors engineering design evaluation and subcontractors). For example, existing studies do not systematically take into account how upstream (executive requirements) factors may affect downstream (detailed level) factors.

Furthermore, there is a lack of implementation or application of advanced requirements management methods (e.g. hierarchical analysis) for the management of multiple levels and multiple dimension requirements. While hierarchical analysis is often facilitated through the application of QFD, their application is limited in scope and depth because they do not consider how multiple sections of a building interact with one another.

The literature review highlights that there are various modularisation tools, but few have been applied to the development of manufactured construction products. Both Gilbert and Veenstra demonstrated the value of modularisation tools and their applicability in construction (Veenstra et al. 2006; and Gillbert III et al. 2014). But, they did not address the nature of the modularisation problem in construction and did not consider the issue of modularisation drivers. Gilbert focused on module functionality (i.e. technical specification), and Veenstra focused on product platforms (i.e. common unit or standardisation). There is a need to consider multiple modularisation drivers in the definition of modules. Although both Gilbert and Veenstra have worked on modular construction, there is a need to undertake research on up market modular products specific to advanced off-site construction and understand how to manage modularisation issues. Despite the existence of various modularisation tools, there is a need to determine which tools would be effective at supporting the development of modular products in construction.

Against the background of the literature review, this research focuses on the application of DSM, MIM, and GVI, which are also more commonly used in other engineering disciplines (e.g. mechanical engineering, robotics, automotive, and consumer electronics) (Borjesson 2010). These three tools are systematic and analytical in nature. They provide benefits in terms of data analytics, allowing for the identification of strategic advantages. DSM is more effective at dealing with dependency issues in product. MIM is specifically designed to incorporate business strategy into product development. GVI combined with another index (e.g. CI) offers one of the most effective ways to determine a product platform.

2.9. Conclusion

This chapter reviewed product planning and complexity management tools, including frameworks applied in construction as well as other industries to understand their potential to support product planning and the design of manufactured construction products. It argues the need to consider the limitations associated with systematic product planning tools and frameworks. It stresses and contextualises the need for developments of tools and frameworks to support advancement of the construction industry. While there are several product planning tools developed outside of construction discipline, their application to construction has been limited.

Studies related to tools for systematic product planning in construction are infrequent. This research emphasises the need for a systematic and analytical approach to advance product planning tools. As such, the research contributes by identifying and applying tools (i.e QFD and modularization tools) for manufactured construction products.

In determining the application of systematic tools, a number of factors were considered in this research (e.g. data-oriented and compatibility with other tools). The literature review provides the justification and benefits for the selection of QFD for requirements management analysis. QFD is also a systems engineering tool and has the benefit of systems and data-oriented values. In determining modularisation approaches, data-oriented methods were considered. In particular, methods integrating modularisation with requirements management tools were suitable. The research focuses on the application and integration of QFD tool with DSM, MIM, and GVI. The latter three tools are systematic and analytical in nature. They provide benefits in terms of data analytics, allowing for the identification of strategic advantages.

Following from the analysis above, the literature review highlights the need for a framework that supports product planning for manufactured construction products. Such framework could provide an integrated approach for product planning by combining requirements information modelling and modularisation for manufactured construction products.

Chapter 3

Research Approach

3.1. Introduction

This chapter explains the overall research approach, which includes data collection, validation approaches and cooperation provided by the collaborating company. It describes extraction of data or information from the collaborating company's documents, interviews, workshops, questionnaires, case studies and evaluations of work activities. The chapter is divided into three main sections: design research methodology (DRM), application of DRM, and approaches for conduct of case studies.

3.2. DRM framework

This research utilised the DRM methodology framework established by Blessing and Chakrabarti (2002) to investigate existing work processes of the collaborating company (with the aim of making improvement to them). The DRM framework has proven to increase project efficiency compared to other research methodology (Blessing and Chakrabarti 2002). Figure 3.1 summarises the four specific stages of the DRM framework applied in this research. The Figure also presents the corresponding research outcomes associated with each stage, which in descending order include goal setting, understanding of the research problem, types of research support and evaluation consideration. The DRM can also relate to basic research classification, which begins with an initial stage of literature review to data analysis, assumption or experience synthesis, to further data analysis. Each stage supports the development of the subsequent stages of the research process.

Each of the four stages of the DRM framework serves specific research objectives. They are explained below:

- Stage 1 relates to *Research Clarification*, which involves examination of the existing process and define success criteria of the study. This stage of the research covers literature review and initial discussion and interview with engineers of the collaborating company to clarify terms, approaches, how and why certain product development were undertaken.
- Stage 2 is *Descriptive Study 1*, which aims to gain an in-depth understanding of the existing process through first-hand experience and analysis of evidence, and identify factors that influence the formulated criteria. At this research stage, workshops and follow up interviews with engineers at the collaborating company were conducted. Working with key engineers at the collaborating company were undertaken. Certain company files and records were reviewed.
- Stage 3 covers *Prescriptive Study*, which defines the process through an increased understanding of the existing process established in Descriptive Study 1. This stage of the framework proposes improvements to reach the desired process. Case study was developed and the results were explained to engineers at the collaborating company through workshops to gain feedback and for validation of approaches.
- Stage 4 is *Descriptive Study 2*, which evaluates the proposed improvement. Feedbacks from the collaborating company were taken into account in the revised and refinements of the case study. Models were evaluated against study objectives and success criteria.

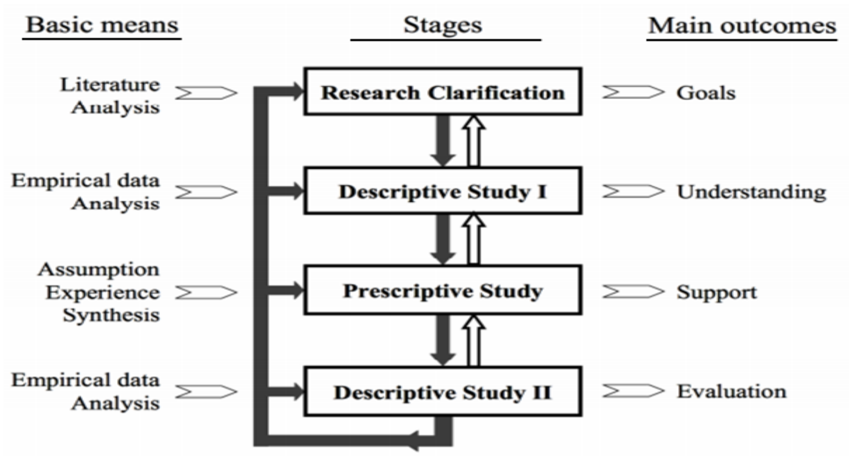


Figure 3.1. The Design Research Methodology (Source: Blessing and Chakrabarti 2002)

3.3. Application of the DRM framework

The research consisted of 19 steps, which involves research clarification, descriptive 1, prescriptive, and descriptive research stages (see Figure 3.2). These steps cover a literature review and five studies (described below). Each stage adds and accumulates information to address complexity management issues in construction. These five studies are interrelated and are described in the respective chapters. An overview of how these studies are related are explained in Section 3.4. The key features of these studies are summarised below:

(i) An initial literature review was conducted, which comprised “research clarification” and “descriptive 1”. It was conducted to determine the scope of issues related to the construction industry and to frame the research problem.

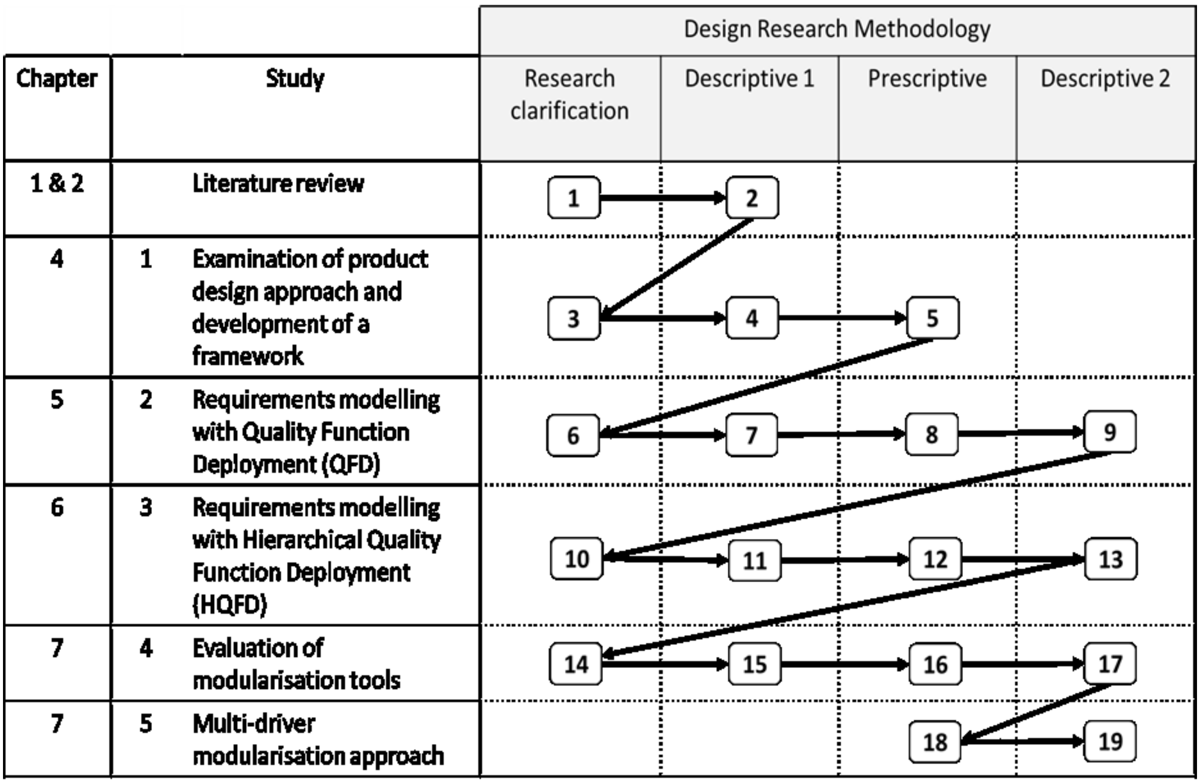
(ii) Study 1 (Examination of product design approach and development of a framework) was undertaken to examine the research problem. The examination looked into issues of flexibility in relation to manufactured construction products. A product complexity management framework was proposed to address the identified research problem. The framework consists of two main features: 1) requirements management and 2) modularisation.

(iii) Study 2 (requirements modelling with Quality Function Deployment) consisted of all DRM stages. The study addressed issues of requirements management and complexity management of a single product type (i.e. plantroom) under manufacturing construction conditions.

(iv) Study 3 (Requirements modelling with Hierarchical Quality Function Deployment) also consisted of all DRM stages. The study addressed issues of requirements management and complexity management that associated with multi-dimension, multi-layer and involves different segments of an entire building.

(v) Study 4 (Evaluation of modularisation tools) specifically addressed the issue of complexity management through the use of modularisation methodology.

(vi) Study 5 (Multi-driver modularisation approach) also addressed the issue of complexity management and identify a suitable modularisation approach.



Note: Numbers in boxes refer to research steps.

Figure 3.2. Research project process

3.4. Case studies

Each of the five studies can be classified into four categories of research, which can range from feasibility, applicability, practicality to scalability. *Feasibility* demonstrates the conceptual soundness of a method or framework by testing it with an engineering dataset. *Applicability* demonstrates the conceptual soundness of the method or framework by receiving acceptance of practicing engineers. *Practicality* demonstrates the conceptual soundness and industrial relevance of the method or framework by testing it with practicing engineers. And *scalability* underlines conceptual soundness, industrial relevance and applicability to a complex project by testing on a large engineering programme in the industry.

Table 3.1 presents the major elements and detailed description of the five studies. It highlights information on parameters, type of research, type of data, methodology, participant, level of complexity, and the case studies. An overview of how these studies are related are covered below.

Table 3.1. Case studies, methods and validations

	Case studies				
	Study 1	**Study 2**	**Study 3**	**Study 4**	**Study 5**
Controlled parameters	**Product management environment and a framework**	**Requirements modelling and analysis**	**Hierarchical requirements modelling and analysis**	**Modularisation analysis**	**Modularisation approach**
Type of research		Feasibility /Applicability /Practicality	Feasibility /Practicality /Scalability /Applicability	Feasibility /Applicability	Feasibility
Data type	Industry	Industry	Industry	Industry	Industry
Method of data generation	NA	i) Reverse engineering (*) ii) Interviews iii) Workshop	i) Reverse engineering (*) ii) Interviews iii) Collaborative work	i) Reverse engineering (*) ii) Interviews iii) Survey	i) Reverse engineering (*)
Participant	NA	i) PhD researcher and 2 LOR engineers ii) Engineers (LOR and RB) iii) LOR engineers (8)	i) PhD researcher and 5 LOR engineers ii) LOR engineers (5)	i) PhD researcher and 5 LOR engineers ii) LOR engineers (3)	i) PhD researcher and 2 LOR engineers
Level of complexity	NA	Medium	High	Medium	Medium
Case study	NA	Plantroom	Apartment buildings, Apartment module, Module frame, Interfaces	Plantroom	Plantroom
Size of dataset	NA	2 QFD matrixes (1 model), Approx. 70 requirements	11 QFD matrixes (6 models), Approx. 300 requirements	3 models: • 16 x 16 DSM; • 15 x 16 MIM; • 29 x 18 GVI;	3 models: • 16 x 16 DSM; • 27 x 27 DSM; • 29 x 18 x 16 x 16 x 16 platform model
Complexity of solution	NA	18 systems	92 systems	18 systems	18 systems

Notes: LOR = Laing O'Rourke; RB = Robert Bird (consultancy company to LOR).

3.4.1. Study 1: Current design approach and framework proposal

This study aims to determine the current design approach at the collaborating company and to propose a framework for efficient, systematic and flexible design of building systems. The framework was developed by undertaking empirical research to understand the practices of the collaborating company and conduct of related case studies. The approach adopted to develop the framework involved three research phases i) understanding the current approach to design modular systems, ii) framework development, and iii) framework evaluation.

3.4.2. Study 2: Requirements modelling through QFD

This study investigates requirements management practices in the construction industry. It proposes and evaluates the application of Quality Function Deployment as a requirements analysis tool for manufactured construction products. The QFD tool was applied using a reverse engineering approach to identify the plantroom requirements. Requirements information was extracted from technical documents, modelled in QFD and subsequently validated during a workshop. The details of this methodology can be found in Chapter 5 (Study 2: Requirements modelling and analysis).

3.4.3. Study 3: Hierarchical requirements modelling through HQFD

This study builds upon the discussion of Study 2 (i.e. Chapter 5). Instead of working on QFD for one product (e.g. plantroom), this chapter discusses the implementation of a large set of inter-related QFDs to address multi-dimensional and multi-layer product requirements. In particular, it focuses on complexity management techniques for large modular systems in construction through the application of Hierarchical Quality Function Deployment (HQFD) model.

The knowledge on requirements analysis and process was expanded to include a new set of construction products segment across a spectrum of requirements levels (see Chapter 6). These products included a whole apartment building, module apartment, module frame, interfacing system, interface rack, plantroom (reused from Study 2) and bathroom pods. Quality Function Deployment (QFD) for each of these product segments were developed. The methods used to develop these QFD models were the same as that covered in Study 2. These QFD models were then integrated to form a Hierarchical Quality Function Deployment (HQFD) model. The details of this methodology are elaborated in Chapter 6 (Study 3: Hierarchical Quality Function Deployment).

3.4.4. Study 4: Evaluation of existing modularisation tools

This study examines the application of three modularisation tools to support efficient development of modular construction products. In particular, it evaluates the application of “dependency structure matrixes” (DSM), “modular identification matrix” (MIM) and “generational variance indexes” (GVI). The tools were applied to the plantroom case study and evaluated for their suitability to support construction operations focussing on the modularisation drivers that they address. Modularisation information was extracted from engineering documents (e.g. product schematics and manuals), as well as interviews with engineers who developed the plantroom. The details of this methodology can be found in Chapter 7 (Study 4: Modularisation analysis).

3.4.5. Study 5: Multi-driver modularisation approach

This study develops an approach for addressing multiple modularisation drivers in construction. The knowledge gained from Study 4 was then used to develop a modularisation approach (strategy). The modularisation drivers addressed in this research include: technical specifications, manufacturing and common unit. Several modularisation matrix and index tools were utilised including design structure matrix (DSM), generational variety index (GVI), coupling index (CI), and Cost indexes. The various tools were utilised for natural clustering and objective driven clustering methods. These modularisation methods were implemented on a plantroom case study. The details of this methodology are explained in Chapter 7 (Study 5: Modularisation approach).

3.5. Conclusion

This research utilised the DRM framework to increase the research efficiency and in data collection. The research employed a number of approaches including reverse engineering and case studies to collect data and information on real manufactured construction products at the collaborating company. The research approach has contributed to the collection of data for the development of requirements management and modularisation methods and models. Information on real construction products were utilised to ensure research validity and accuracy. The development of models and examination of cases were undertaken in collaboration with expert engineers of the collaborating company.

Chapter 4

A Framework for Product Planning and Complexity Management

4.1. Introduction

This chapter examines the product design approach and product management environment of the collaborating company to help develop a framework for product planning and complexity management. Based on understanding of the practices of the collaborating company, there are design gaps that limits the ability of the company's existing system to effectively capture and analyse product requirements. Following from this investigation, a framework was developed to support efficient, systematic and flexible design of building systems. The proposed framework consists of an integration of QFD tools to address requirements management (see Chapters 5 and 6) and modularisation approach (Chapter 7).

Components of the framework were subjected to evaluation and validation exercises that involved discussions with and questionnaire responses from the company's engineers on requirements analysis and modularisation. A workshop was also conducted to evaluate the usefulness of requirements analysis tool, which is a component of the framework. The results support the functionality of the framework for product planning and complexity management through requirements management (see Chapter 5) and modularisation tools (see Chapter 7). These two sets of tools and their usefulness were examined in detail in Chapters 5 and 7.

The chapter begins with an analysis of approaches and product designs used by the collaborating company. It then explains the requirements needed to develop a product planning framework and the components of the framework.

4.2. Methodology

In developing the framework, a number of interrelated steps were followed to understand the product design approach and environment of the collaborating company, design gaps and how the gaps can be addressed. An empirical research to understand the practices of the collaborating company and case study were conducted. The methodology adopted involves three research phases as described below.

(i) Understanding the current approach to design modular systems

At the start of the research, design documents were examined, and meetings were held with expert engineers at the collaborating company to determine the approach in designing modular systems. It involved examination of existing product documentation and discussions with engineers. Topics investigated during this study included design processes, product portfolios and product technical issues. An extensive review of documents centred on plantroom design was performed. These documents included CAD files, schematics, bills of materials, product manuals, and requirements documentation.

Fifteen informal discussions, which lasted between 15 and 120 minutes, were also carried out with different groups of engineering experts to investigate plantroom design processes and validate existing understanding of the collaborating company's engineering operations. These discussions took place at the collaborating company's main design offices and factories as part of periodic visits and a one-week secondment. Notes were taken in all discussions and compiled into a notebook for analysis. The experts interviewed included mechanical engineers, design engineers and systems engineers who worked on plantroom products. The data collected was reviewed to understand product functionality, product features, design rationale and the current design procedure.

In addition, the research was involved with an internal initiative to introduce a product configurator, as it is a key tool for management of modular products. A model was subsequently developed to show how a product configurator could be used to manage modular products under the existing business and operational requirements of the collaborating company. The data upon which the model is based was collected through three meetings with the collaborating company's plantroom design leader. This model was then enhanced and validated with a week secondment at the company during which the researcher was given a demonstration of the product configurator by three systems engineering consultants and two engineers from the collaborating company.

(ii) Framework development

Based on the insights and lessons gained from "understanding the current approach to design modular systems" of the collaborating company, the requirements for a product planning framework were identified (e.g. consideration to support product requirements analysis and prioritisation). Identifying and understanding the gaps of the existing system were useful for the development of the framework. A framework that integrates tools for requirements management and modularisation was developed. The former covers QFD tools, which are explained in detail in Chapters 5 and 6, and the latter is elaborated in Chapter 7.

(iii) Framework evaluation

The framework was subsequently evaluated using: i) a live case study of a chilled water modular plantroom product (see Figure 4.1), ii) a workshop and iii) interviews with the collaborating company's engineers. The case study was used to produce models of the plantroom requirements and modularise its design, while the workshop and the interviews were conducted to gather feedback. The results of these evaluations are explained in detail in Chapter 5 (Study 2: Requirements modelling and analysis) and in Chapter 7 (Study 4: Modularisation analysis MEP and Study 5: Modularisation approach).

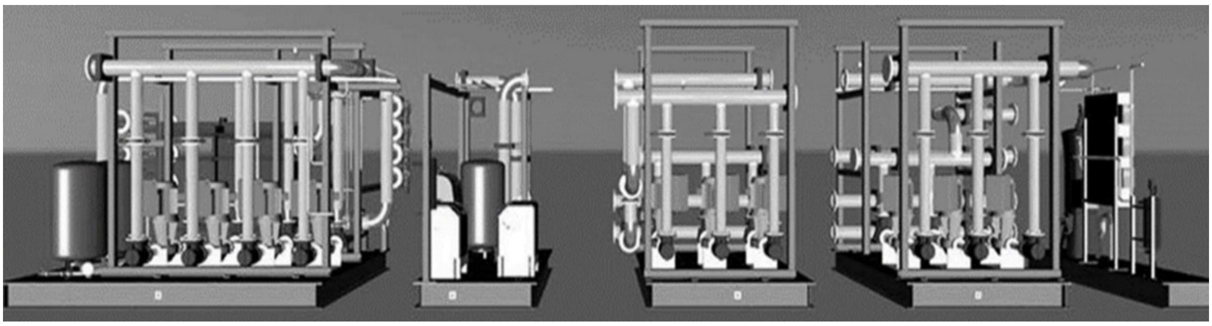


Figure 4.1. Modular chilled water plantroom (Source: Laing O'Rourke)

4.3. Current design approach

The current design approach of the collaborating company in developing plantrooms is based on an iterative process, heavily reliant on the engineering expertise of the design team. It revolves around understanding key product features such as duties, locations and purpose of use and then developing a product schematic followed by a CAD model. To support the design process of plantrooms, the collaborating company has developed a 'step-by-step' procedure listing key considerations. The design process is carried out by internal design teams and external collaborators, and it focuses on design, systems, and structural and software issues.

Figure 4.2 illustrates the design process currently utilised by the collaborating company. The requirements for plantrooms are typically attained from initial discussions with clients, consultants and experts. These requirements are oriented towards meeting specific industrial standards or client's requests rather than emphasising on product functions. The requirements are listed in a requirements document covering multiple product typologies. The requirements document does not distinguish different types of requirements and it does not capture the relationships between requirements and product systems. The requirements document consists of a list of items derived from design discussions. There is an apparent need for tools to support more effective capture and systematic analysis of requirements.

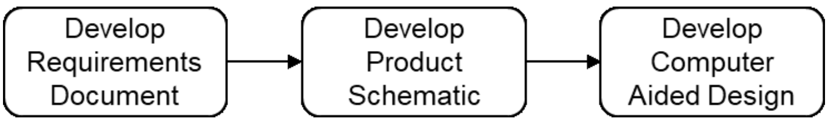


Figure 4.2. The current design process

A number of key observations and findings emerged from the analysis of design practices of the collaborating company. They include the following:

- A shift is occurring in the collaborating company's practices from design for on-site to design for off-site construction (see Chapter 1).

- Requirements management are typically captured in project briefs. Instances of more formal and systematic capture and analysis of requirements exist but they are infrequent.
- A product configurator is increasingly seen as useful support to manage designs. However, the product configurator, commonly adopted in industries such as the automotive (Gann 1998), is still new to the construction industry. The basic function of a product configurator involves clients or engineers inputting product requirements and preferences to drive the selection of modules from a library. A schematic illustration of a product configurator appears in Figure 4.3.

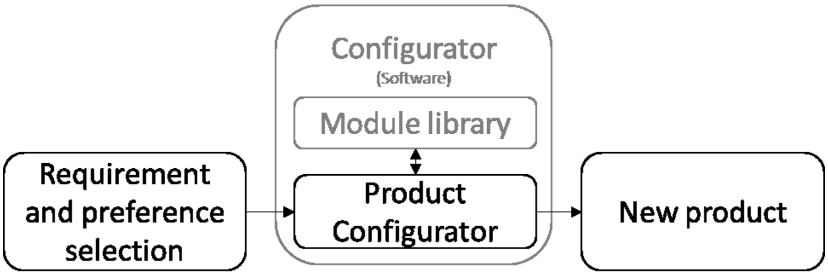


Figure 4.3. Product configurator

4.4. Framework requirements

The observation on current design approaches of the collaborating company, shows that a gap exists between the shift towards off-site construction and the introduction of a product configurator. Specifically, there is a need to support a more effective product planning to help define a library of modules. For this purpose, a framework to guide engineers in requirements management and product modularisation is required. The specific requirements of the framework are presented in Table 4.1.

Table 4.1. Framework requirements

Requirements	Justification
Guide engineers in product planning	Product planning is key to achieve increased industrialisation. The issues of product quality and product flexibility have to be solved simultaneously and in an integrated manner. A product planning framework needs to ensure product quality and flexibility through effective capture of requirements and definition of product variation.
Guide engineers in requirements analysis and prioritisation	The construction process involves multiple stakeholders, high levels of uncertainty and interconnected requirements for new building projects. Guiding engineers in systematic requirements management practices is crucial to ensure product quality.
Guide engineers in product modularisation	The construction process involves large product variation, which are a main source of risk for delivering product flexibility. Guiding engineers in systematic modularisation practices is crucial to ensure product flexibility.
Integrate with a product configurator	The construction process is shifting towards the automatic definition of product configurations from existing libraries of product options and the framework has to support this objective.
Support and integrate with the RIBA process	The construction process is organised and managed by the Royal Institute of British Architects (RIBA) plan of work and the framework has to fit within this context.

4.5. A proposed framework and its components

An effective product planning framework for modular product can help guide the development and management of manufactured products. The proposed framework integrates tools for product planning, which involves requirements management and modularisation. This is intended to address production of a single construction product to be manufactured in a factory environment and to achieve flexibility in design to reduce product redesign risks or to achieve product flexibility (see Figure 4.4). The first part of the framework looks at requirements management and prioritisation through the utilisation of QFD tool (see Chapters 5 and 6). The second part looks at product modularisation, which involves utilisation of the DSM, MIM and index tools (e.g. GVI and CI) (see Chapter 7).

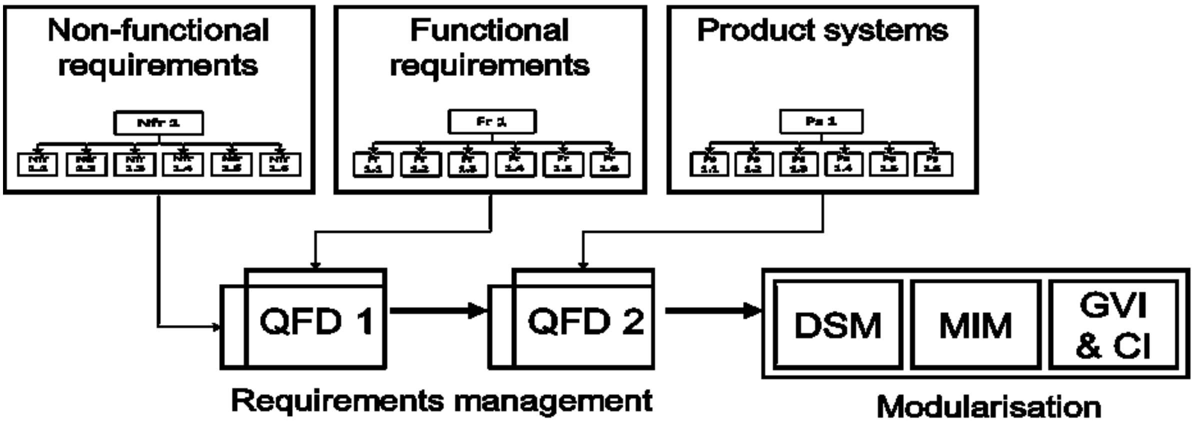


Figure 4.4. Product planning framework for modular building systems

Analysis of requirements management can be supported with QFD tool, which is to capture and analyse requirements arising from multiple disciplines. QFD tool was selected for it's comprehensive, systematic and data orientated features, as well as its compatibility with various modularisation tools (e.g. DSM and GVI). The justification for the selection of QFD tool is explained in detail in Chapter 2. The tool is used to map non-functional requirements to functional requirements and then to product systems. Modularisation allows the design of flexible product systems using strategic clustering of product components, which also is used for complexity management of product systems.

Requirements management is important to develop quality modular products. The systematic mapping and organisation of product requirements to product systems is an important prerequisite for modularisation. QFD tool is employed to facilitate this mapping, which allows systematic development of new products in accordance to the requirements for new product introduction. QFD tool also provides an environment for understanding engineering design rationale across different product representation and their interdependencies. The QFD tool supports the implementation and prioritisation of requirements and product systems. Prioritisation is an important part of the framework as it covers the organisation of product requirements to meet established objectives for mass-customisation. It is useful to understand the shortfall between the current bespoke construction business and the desired mass-customisation outcome. As a result, prioritisation helps identify where it would be best to place a company's resources for higher returns on investment.

Modularisation involves identifying clusters of product components. It helps reduce design risks and increase flexibilities of a product or production system (Koh 2015). A modular problem can derive from a series of different modularisation drivers. It is important that the correct tools are selected to address the right modular driver. The modularisation aspect of the framework looks at utilising several tools to best address the modularisation problem. When correct tools for the problem are utilised, the modularisation problem can be solved adequately. This allows for more effective modules to be developed, which reduces the amount of effort needed for redesign. It is recommended to implement a data oriented and multi-driver modularisation approach to maximise the strategic advantages that modularity brings.

Evaluation of the framework components with engineers and from a workshop confirms the usefulness of the framework for complexity management of singular modular construction products. The QFD component of the framework was more systematic, precise and insightful than the current requirement management methods used at the collaborating company (see Chapter 5). The modularisation aspect of the framework presented more detailed and more targeted modulation solutions (see Chapter 7).

4.6. Discussion

The need for a framework to support systematic capture and analysis of product planning is also corroborated by the lack of such framework for the construction industry. For instance, a limited number of past studies has applied modular product planning frameworks to construction projects (Veenstra et al. 2006; and Gilbert III et al. 2013). However, these studies have employed methods from other research fields that were not specifically adapted for construction and as such they have limitations (see Chapter 2).

The examination of the collaborating company's practices indicates that there is a need for a more effective product planning system or framework to help define a library of modules and modular products. A product planning framework should be able to guide engineers to meet certain requirements. They include i) guide engineers in product planning, ii) guide engineers in requirements analysis and prioritisation, iii) guide engineers in product modularisation, iv) integrates with a product configurator, and v) supports and integrates with the RIBA process. Taking into account these requirements, a framework for product planning and complexity management was developed to achieve efficient, systematic and flexible design of building systems. The framework consists of an integration of QFD and modularisation tools.

The proposed framework takes a more tailored structure to address complexity management of manufactured products in construction. It provides a comprehensive and advanced tool to analyse requirements and modular designs. It specifically uses a functional approach to QFD to introduce more rigour in the way requirements are organised and analysed. In this regard, the proposed framework is expected to support a deeper understanding of product planning for complexity management in construction than those proposed in existing literature such as in Veenstra et al. (2006) and Gilbert III et al. (2013) (see Chapters 5 and 6). It also suggests how to formulate modular solutions by tackling multiple drivers relevant to the specific problem at hand (e.g. technical specification and common unit) (see Chapter 7).

4.7. Conclusion

This chapter has described the challenges in developing product planning tools for complexity management in the construction industry, drawing on observations from the collaborating company. Based on understanding the product planning environment of the collaborating and the design gaps, a product planning framework was developed. The framework emphasises the need for an integrated approach through implementation of methods for requirements management and modularisation. The novelty of the framework lies in the integration of tools to achieve efficiency and flexibility simultaneously to support manufactured construction products.

Chapter 5

Requirements Modelling through Quality Function Deployment

5.1. Introduction

At a process level, increased industrialisation primarily necessitates robust product planning by introducing requirements management and analysis practices. Product planning prevents logic holes, lost resources and indicates pathways to achieve engineering targets (Wee et al. 2017a). In the construction industry due to the fragmented nature of the product development process with multiple stakeholders involved, it is often challenging to capture the complex and interconnected requirements for new building projects (Kamara et al. 1999; and Gilbert III et al. 2014). In addition, the current approach to designing tend to focus on deploying functional product solutions, rather than investing time in requirements analysis with advanced tools (Wee et al. 2017a).

This research is concerned with supporting organisations in the construction industry to become more requirements-oriented (i.e. systematically develop new products according to the principles of validating a design solution against the requirements captured and engineered at all levels). The utilisation of modular building products in construction is critically dependent on the development of effective requirements management and analysis practices (Wee et al. 2017a). It is therefore essential to select a requirements analysis tool that is systematic and that can integrate with additional modularisation tools. Against this background, the aim of this research is to propose and evaluate a requirements analysis tool to support advanced off-site construction.

This chapter explains the implementation of QFD, a systematic tool for the management of product requirements associated with multiple stakeholders, to a modular construction plantroom. QFD was selected as it can integrate with other matrix style modularisation tools for increased impact on construction operations (Wee et al. 2017a).

Using a reverse engineering approach, a QFD model of a plantroom design was developed. The plantroom requirements were derived from the analysis of CAD models, schematics and other requirements documents. The model was further validated with experts from the collaborating company and other organisations in their supply chain. The QFD model maps the non-functional requirements of a product to its functional requirements and then to product systems (Wee et al. 2017b).

The novelty of the model proposed in this research lies in the implementation of a functional approach to QFD based on the systems engineering information model proposed in (Burge 2007) and how QFD has been tailored and organised to handle the requirements of modular products for off-site construction. The model addresses three important issues: systems engineering modelling of construction requirements, multi-stakeholder organisation, and requirements prioritisation for the identification of industrial shift shortfall. QFD offers an opportunity for prioritisation by determining requirements importance for achieving modular construction. In addition, prioritisation is valuable for determining which requirements are unique to new state of the industry.

5.2. Methodology

Data collection: The data collection for this study involves two steps the i) examination of existing documentation, and ii) extraction of requirements information from engineers:

i) **Examination of existing documentation:** An extensive review of documents on the plantroom case study was conducted at the collaborating company to understand the various product features and design decisions made by the company. The information collected was used to identify requirements. The documents reviewed include CAD files, schematics, bills of materials, product manuals and requirements documentation.

ii) **Extraction of requirements information from engineers:** Several interviews and discussions with engineers at the collaborating company were conducted to obtain information on design process, product requirements and design rational. These interviews and discussions are described in Chapter 4 which investigate plantroom design processes and validate existing understanding of the collaborating company's engineering operations

Model development: A QFD model of an industrial chilled water plantroom was developed employing a reverse engineering approach. The overall structure of the QFD model including the QFD1 and QFD2 matrixes is illustrated in Figure 5.1. The QFD model utilises an information model that was adapted from Burge (2007) and Curwen (1991). Compared to the information models normally applied in QFD research, the model applied to the water plantroom is functionally oriented and in line with the principles of systems engineering. More so, the information model supports functional thinking and functional based modularisation. The information model includes three main information types, namely *non-functional requirements, functional requirements* and *product systems (*see Figure 5.1*).*

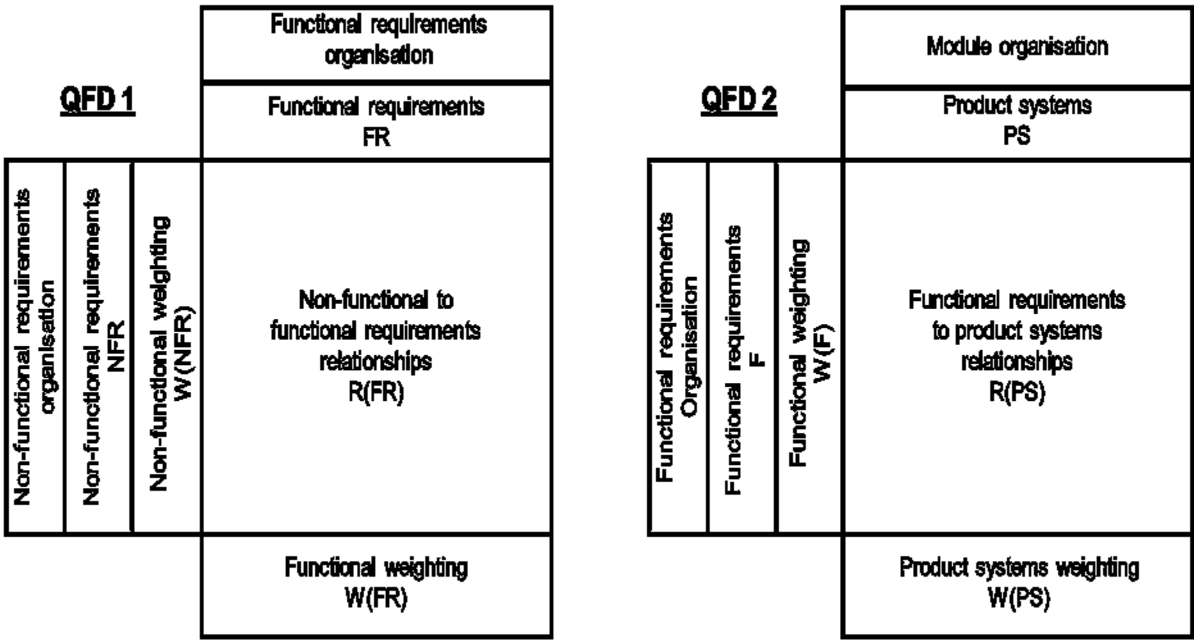


Figure 5.1. Overview of QFD model

Non-functional requirements refer to whole system characteristics of the product, while functional requirements refer to the demands on product functionality, and product systems refer to the main groups of components forming the architecture of the product. Product systems and functional requirements were respectively identified and inferred by reviewing engineering documents such as CAD files and product schematics. Functional requirements and product systems were subsequently mapped onto QFD 2. Non-functional requirements were identified from a deep exploration of plantroom whole system characteristics. The non-functional requirements were then organised in a hierarchical structure according to stakeholders' demands. Non-functional requirements and functional requirements were then mapped onto QFD 1 and their relationships assigned one of three possible values (i.e. 1: weak; 2: medium; and 3: strong). The weighting of the non-functional requirements was determined by an iterative process of understanding the collaborating company's objectives and those for advanced off-site construction. The outcome was then validated through discussion with a leading engineer at the collaborating company. The weighting of the non-functional requirements is captured by one of three possible values (i.e. 1: low importance; 2: medium importance; and 3: high importance).

The weighting of the functional requirements and product systems was calculated as per equations 1 and 2 where:

- W(Fr)x (the calculated weighting of a 'functional requirement' with reference number x in QFD1) is determined by the product-sum of all associated $\mathrm{W(Nfr)}_y$ (the assigned weighting of a non-functional requirement with reference y in QFD1) and $\mathrm{R(Fr)}_{xy}$ (the weighting of a relationship between the non-functional requirement with reference y and the functional requirement with reference x), and;
- W(Ps)y (the calculated weighting of each 'product system' with reference y in QFD2) is determined by the sum-product of all associated $\mathrm{W(Fr)}_z$ (the assigned weighting of a functional requirement with reference z in QFD2) and $R(Ps)_{yz}$ (the weighing of the relationship between a functional requirement with reference z and product system with reference y).

$$\mathrm{W(Fr)}_x = \sum(\mathrm{W(Nfr)}_y \times \mathrm{R(Fr)}_{xy}) \quad (1)$$

$$W(Ps)_y = \sum(W(Fr)_z \times R(Ps)_{yz}) \quad (2)$$

Model evaluation: The QFD model was evaluated in two steps. First, seven interviews were conducted with experts at the collaborating company (3) and external consultants (6). The interviewees had engineering experiences ranging from 4.5 to 40 years. Of the interviews, five were audio-recorded and the other two were documented using hand written notes.

Second, a workshop was conducted with a group of engineers (8) at the collaborating company to assess the value of the QFD tool to the business. The workshop started with a presentation of the QFD model by the research team. The participants were then invited to discuss the usefulness and applicability of the method as well as its potential benefits and limitations. Towards the end of the workshop participants were administered a survey questionnaire. An example of this questionnaire appears in appendix 1. The questionnaire included 14 questions on the topics of accuracy of the QFD model and its potential benefits.

5.3. Results: the QFD model

A functional oriented QFD model was developed to capture, structure and analyse the requirements of a modular plantroom. The structure of the developed QFD follow that described in Figure 5.1. The QFD model consists of 40 non-functional requirements, 29 functional requirements and 18 product systems (see Figures 5.2, 5.3 and 5.4). QFD1 and QFD2 include 337 and 79 relationships respectively.

Stakeholders			Non functional requirements (demands)		Target values	Priority	In-take water	Cool water	Supply chilled water	Control water temperature	Depressurise water	Control delivery water flow	Control chiller water flow	Sense operating conditions	Prevent instabilities	Maintain operating limits	Communicate with user interface	Prevent accidental impact damage	Protect system against freezing damage	Protect system from electrical damage	Protect from pressure damage	Protect system from corrosion	Maintain seal system integrity	Maintain cooling systems integrity	Maintain water distribution capability	Maintain systems pressurisation capability	Filter impurities and waste	De-gas water	Support plantroom spines	Support module frames	Support plantroom components	Location of spine frame	Secure Internal Pipeing	Ensure system plantroom alignment capability	Secure plantroom module with in building	
			Functional requirement				Primary functions											Secondary functions																		
							Deliver cool water			Control water temperature	Control water pressure	Control water flow		Monitor plantroom operating conditions				Protect plantroom from damage					Ensure product integrity				Clean water systems		Frame components					Ensure system compatibility		
								°C		°C	Bar	L/s	L/s																							
								6	4MW	6 to 12	1, 6,16, 25 or 40	180	180			4MW	BACNet						35 years	35 years	35 years	35 years										
Architecture company	Product & interfaces	Compatbility	Product -building interfaces			2																												3	3	12
			Aesthetic & color			1																							3	3						6
Construction company	Product	Design	Unit cost	£	260000 max	3		3	3	3	3	3	3	3			3	2	2		3	1					3	3	3	3	3		3	1	1	156
			Size	WxHxD (m)	3.5 X 8 X 3.2	3																							3	3	1	1	1			27
			Weight	Tones	35	2	3	3	3	3	3			1													3	3	3	3	3	3	3			74
			Variable temperature	°C	6 to 12	2		1		3																										8
			Energy efficiency		--	3	3	3	3	3	3	3	3	3																						72
		Quality	Complies with regulations & standards			3		3	3	3	3	3	3	3	3	3		3	3	3	3	3	3	3	3	3	3	3								180
			Material selection			2												3	3	3		3							3	3	3		3			48
			BMS requirements			3				3	3	3	3	3			3																			54
			High finishing quality	#finishing flaws		2											3	3	3	3		3					3	3	3	3	3	3	3	3	3	84
			High max power	MW	4MW	3			3							3																				18
		Design Flexibility	Permutaion options	#		1	1	1	1																				3	3	3	3				15
			Upgrade potential			1	1	1	1																		1	1	3	3	3	3				17
			Module Interface designs	standard design		1	3		1																		1	1						3	3	12
			Degree of modularity		90%	2	1		1	1	1	1																			3	1	3			24
			Percentage of standard parts	%	90%	3		3	3	3	3	3	3	3													3	3	3	3	3		3			117
	Production	Manufac turing	Low total number of parts	#parts		2			3	3	3			3			3										3	3	3	3	3		3	3	3	78
			Manufacturability			3																							3	3	3	3	3			45
			Low number of installation orientatic	#		1																							3	3	3	3	3		3	18
		Assembly	Assembly time targets	time	--	3																							3	3	3	3	3			45
			Assembly cost targets	cost	--	3																							3	3	3	3	3			45
			Assembly capacity targets	capacity		2																							3	3	3	3	3			30
			Assembly sequencing			2																							3	3	3	3	3			30
			Build type	vertical, horizotal	Layered	1																							3	3	3	3				12

Figure 5.2. Part 1 of QFD 1 model

Stakeholders			Non functional requirements (demands)		Target values	Priority	Primary functions											Secondary functions																		
							Deliver cool water			Control water temperature	Control water pressure	Control water flow		Monitor plantroom operating conditions				Protect plantroom from damage					Ensure product integrity				Clean water systems		Frame components					Ensure system compatibility		
						Functional requirement	In-take water	Cool water	Supply chilled water	Control water temperature	Depressurise water	Control delivery water flow	Control chiller water flow	Sense operating conditions	Prevent instabilities	Maintain operating limits	Communicate with user interface	Prevent accidental impact damage	Protect system against freezing damage	Protect system from electrical damage	Protect from pressure damage	Protect system from corrosion	Maintain seal system integrity	Maintain cooling systems integrity	Maintain water distribution capability	Maintain systems pressurisation capability	Filter impurities and waste	De-gas water	Support plantroom spines	Support module frames	Support plantroom components	Location of spine frame	Secure Internal Pipeing	Ensure system plantroom alignment capability	Secure plantroom module with in building	
								°C		°C	Bar	L/s	L/s																							
								6	4MW	6 to 12	1, 6,16, 25 or 40	180	180			4MW	BACNet						35 years	35 years	35 years	35 years										
Building management company	Building management	Reliabilty	Lubricant and contaminant operational levels	#		1																					3	3								6
			Disruption limits	#	--	2	3	3	3	3	3	3	3	1	3	3	1						3	3	3	3	1	1								86
			Performance retention	deterioration rate		2	2	2	2	2	2	2	2	3	3	3							3	3	3	3	1	1								74
			Waterproofing	presure test		2																	3													6
			Resistance to environmental change			2												3	3	3	3	3														30
		Maintainability	High accessibility			2																							3	3	3	3	3			30
			Shutdown sequence for maintenance	# actions		2	3		3		3	3	3					3	3	3	3	3	3													66
			Easy maintainability	time to set up		2	3	3	3	3	3	3	3	3	3	3	3	1	1	1	1	1					3	3	3	3	3	3	3			118
			Cost effective maintenance plans	£	--	2	1	1	1	1	1	1	1	1	1	1	1										3	3	3	3	3	3	3			64
			Component life-span	Time (Years)		2	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3														96
			Product disposal	yes/no		1																							3	3	3	3	3		3	18
			Replacement capability			3										1	2												3	3	3	3	3	1	3	66
		Operations	Health human factors (safety)			2										3	3										3	3	3	3	3	3	3			54
			Ease of use (dexterous unit control)	Time		2											3																			6
		Transport-ability	Safe transportantion for products			3												2											3	3	3		1			36
							52	70	92	89	89	77	75	75	35	53	64	53	47	41	38	44	33	21	21	21	72	72	150	150	147	104	132	27	39	

Figure 5.2. Part 2 of QFD 1 model

					Product systems	Secondary system (dilivery)						Primary system (chiller)					Heat exchanger system	Interphase	Cleanning systems	Electronics		Structure	Piping system	
	Functional requirements			Target value	Wght	3 Way-valves	VT Pump set	Dosing-pots 1	CT Pump set	Degasser 1	Pressure control 1	Primary pumping system	Chiller connections	Dosing pots 2	Pressure control 2	Degasser 2	Heat exchanger	Interphase	Filltration	User interface	Sensors and wiring	Structure	Piping system	Count
Primary functions	Deliver cool water	In-take water			52		2		2															2
		Cool water	°C	6	70	2							1				2							3
		Supply chilled water		4MW	92		2		2															2
	Control water temperature	Control water temperature	°C	6 to 12	89	2							1				1							3
	Control water pressure	Depressurize water	Bar	1, 6,16, 25 or 40	89						2				2						2			3
	Control water flow	Control delivery water flow	L/s	180	77		2		2											1	2			4
		Control chiller water flow	L/s	180	75							2								1	2			3
	Monitor plantroom operating conditions	Sense operating conditions			75																2			1
		Prevent instabilities			35		1		1			1									2			4
		Maintain operating limits		4MW	53		1		1			1									2			4
		Communicate with user (interface)		BACNet	64															2	2			2
Secondary functions	Protect plantroom from damage	Prevent accidental impact damage			53																	2		1
		Protect system against freezing damage			47																		1	1
		Protect system from electrical damage			41																2			1
		Protect from pressure damage			38						2				2									2
		Protect system from corrosion			44			1		1				1		1			2					5
	Ensure product integrity	Maintain seal system integrity		35 years	33	1	1	1	1	1	1	1	1	1	1	1	1	1	1				2	15
		Maintain cooling systems integrity		35 years	21	2											2				1			3
		Maintain water distribution capability		35 years	21		2		2									1			1			4
		Maintain systems pressurisation capability		35 years	21						2				2									2
	Clean water	Filter impurities and waste			72														2					1
		De-gas water			72					2						2								2
	House components	Support plantroom spines			150																	2		1
		Support module frames			150																	2		1
		Support plantroom components			147																	2		1
		Location of spine mounts			104																	2		1
		Secure internal piping			132													1				2	2	3
	Ensure system compatibility	Ensure plantroom system alignment capability			27													2				2		2
		Secure plantroom module with in building			39													1				2		2
						4	7	2	7	3	4	4	3	2	4	3	4	3	3	3	10	6	3	

Note: Wght= weighting

Figure 5.3. QFD 2 model

Non-functional requirements (NFR): In product development processes involving multiple stakeholders such as building construction it is crucial that in the early design stages the requirements of each stakeholder are accounted for as much as possible. The non-functional requirements were organised in a hierarchical structure, see Figures 5.2 and 5.4. At the first level, the stakeholders are listed. At the second level, viewpoints are assigned to the stakeholders. At the third level, individual requirements groups are linked to the viewpoints.

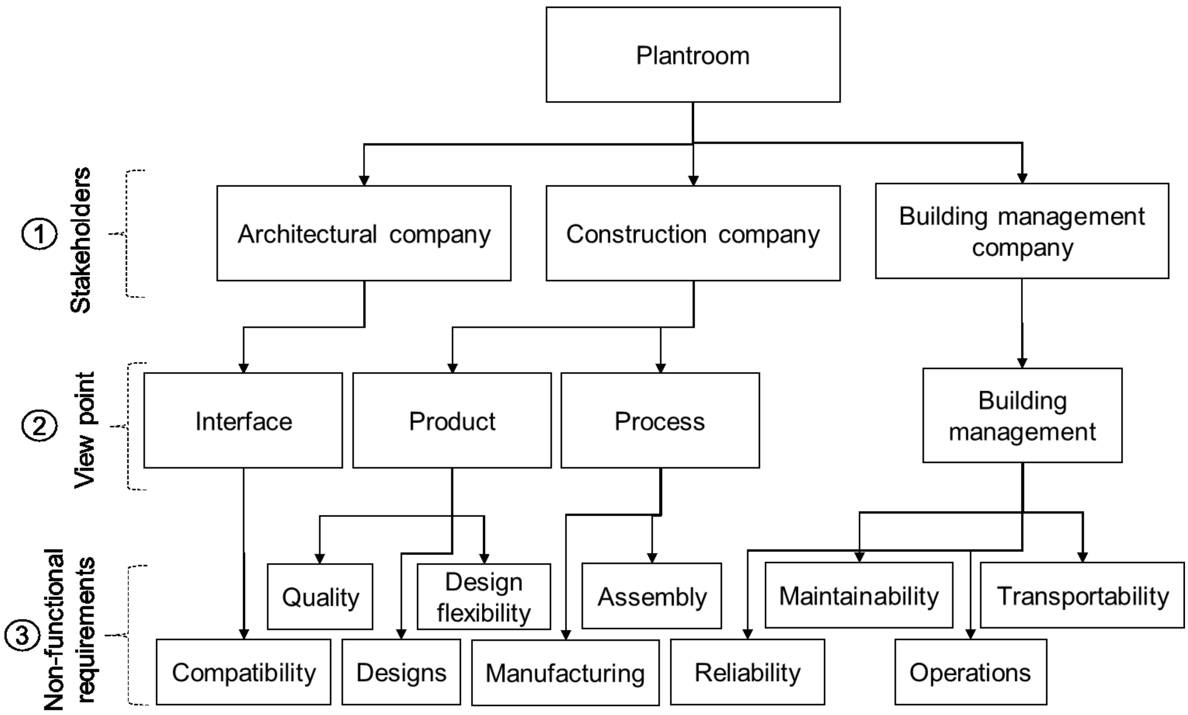


Figure 5.4. Hierarchical organisation of non-functional requirements

The three main stakeholders in the plantroom design are the architectural design company responsible for the building in which the plantroom will be located, the construction company responsible for the plantroom design and manufacturing of it and the building management company responsible for the operation of the plantroom. Figure 7 illustrates the viewpoints of the stakeholders, which comprise issues covering 'interfaces', 'product', 'process' and 'building management'. Examples of non-functional requirements under the 'design' group include 'size' (target value: 3.5 m x 8 m x 3.2 m) and 'variable temperature' (target value: 6 °C to 12 °C). A further example of non-functional requirement under the 'design flexibility' group is the ‘degree of modularity’ (target value: 90%).

The prioritisation of the non-functional requirements was determined by their likelihood to lead to the success or failure of the product under industrialised construction (i.e. advanced manufacturing and modular design) condition. Among the non-functional requirements marked as very important include ‘unit cost’, ‘size’, ‘energy efficiency’, ‘compliance with regulations and standards’, ‘high max power’, ‘percentage of standard parts’, ‘manufacturability’, ‘assembly time target’, ‘assembly cost targets’, and ‘safe transportation’.

Functional requirements (FR): Functional requirements were organised into primary and secondary functions (see Figure 5.5). Primary functions are those that directly target the main function of the product, i.e. deliver chilled water. Secondary functions are those that have a supporting role. Primary functions were organised into various groups, which include 'deliver cool water', 'control water temperature', 'control water pressure', 'control water flow' and 'monitor operating conditions'. Secondary functions were organised into 'protect plantroom from damage', 'ensure product integrity', 'clean water systems', 'frame components' and 'ensure system compatibility'. Examples of functional requirements are 'cool water' (target value: 6 °C), 'depressurize water' (target value: 1-40 bar) and 'maintain operating limits' (target value: 4 MW).

According to their accumulated prioritisation weighting, the four most important functional requirement groups were 'frame components', 'monitor plantroom operations', 'protect plantroom from damage', and 'deliver cool water'. These top four functional requirements belong to the 'frame components' group, which includes ‘support plantroom spines’, ‘support module frame’, ‘support plantroom components’, and ‘locate spine frame'. The ‘frame components’ group is highly valued because of its critical role in satisfying non-functional requirements such as 'design flexibility’, ‘manufacturing’, ‘assembly’ and ‘transportation’.

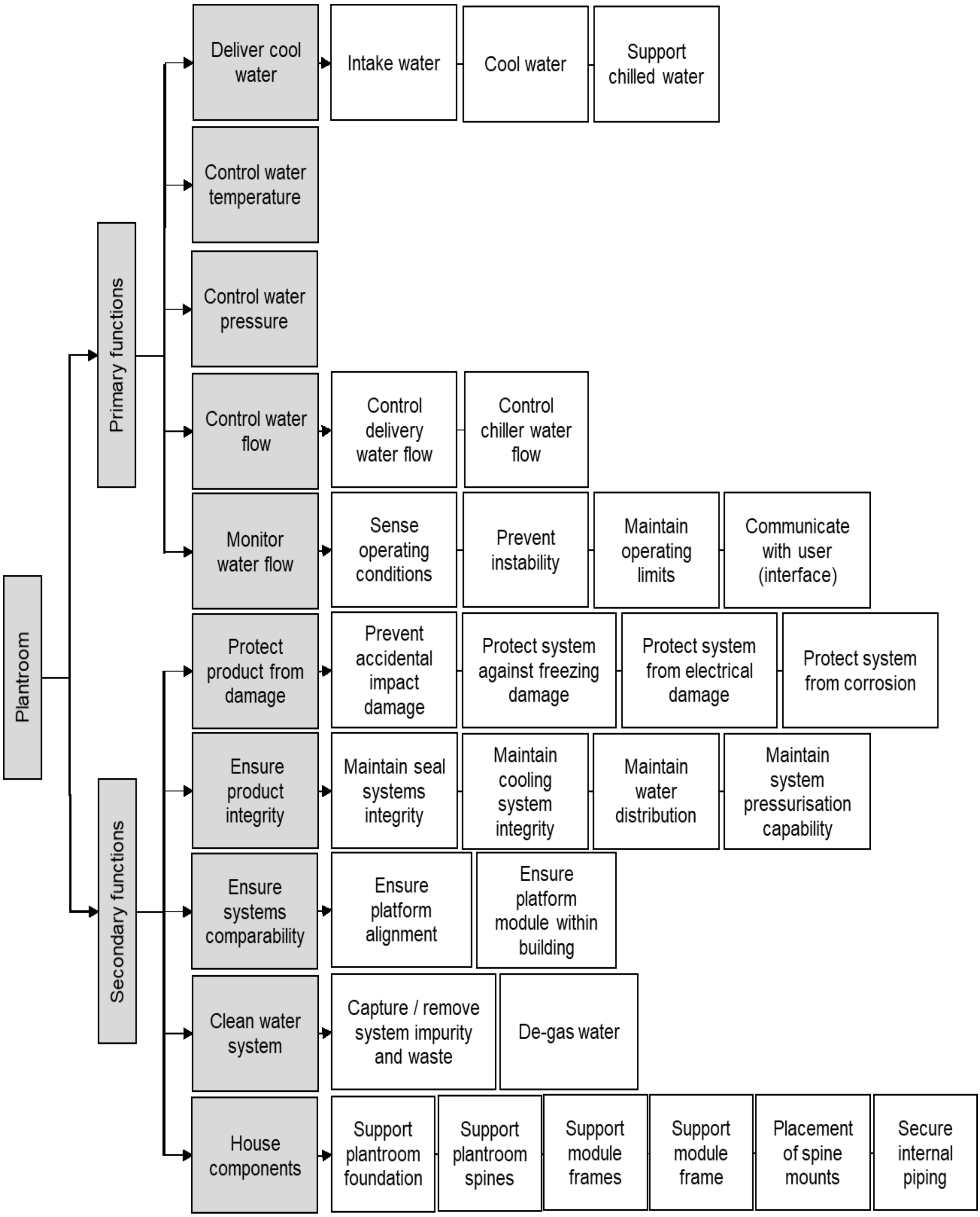


Figure 5.5. Hierarchical organisation of functional requirements

Relationships between non-functional and functional requirements: The relationships between the two sets of requirements are extensive and their identification required significant consideration. Examples of such relationships are presented in Table 5.1.

Table 5.1. Examples of non-functional to functional requirements relationship

Example	Non-functional requirements	Functional requirements	Weighting
1	Variable temperature	Cool water	1
		Control water temperature	3
2	Product-building interfaces	Ensure system plantroom alignment capability	3
		Secure plantroom module within building	3
3	Safe transportation for products	Prevent accidental impact damage	2
		Support plantroom spines	3
		Support module frames	3
		Support plantroom components	3
		Secure internal piping	1

Product systems: The product systems hierarchy was organised into 'delivery systems', 'chilling systems' and 'passive systems' (see Figure 5.6). Examples of product systems include different types of pump series, degasser systems, filters and support structures. These product systems were further organised into different modules.

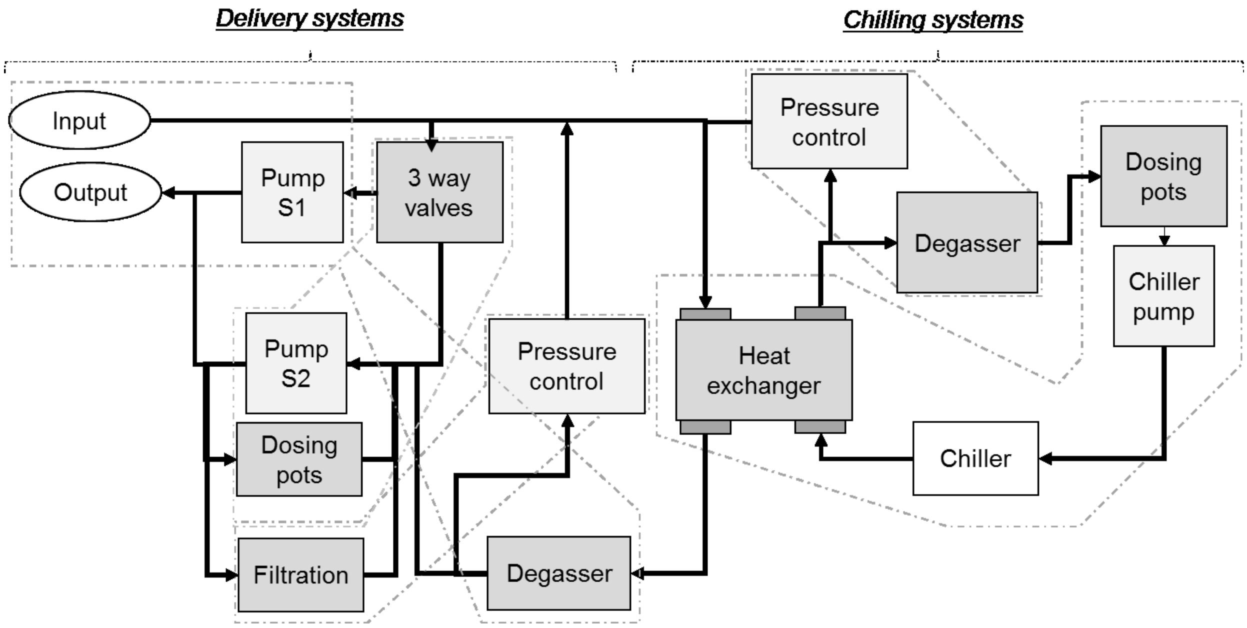


Figure 5.6. Simplified schematic of the chilled water plantroom

Prioritisation analysis: Prioritisation is a valuable feature of QFD. It is especially valuable for the allocation of resources and determining the requirements change for an industry shift in the construction industry. Figure 5.7 highlights the design importance of the plantroom product functional requirements under industrialised construction (i.e. advanced manufacturing and modular design) condition. It illustrates (indicated in blue) the common design importance between bespoke construction and industrialised construction operation. What is left (in orange) is the shortfall in requirements fulfilment needed to achieve mass-customisation. In order to move from bespoke to advanced modular construction, there is a need to increase the engineering effort placed on the design frame or structural components, as they are more likely to yield higher potential result. This result is due to the manufacturing, assembly, design flexibility and transportation non-functional requirements that do not normally occur in traditional bespoke construction, which are mainly satisfied by structural frames design.

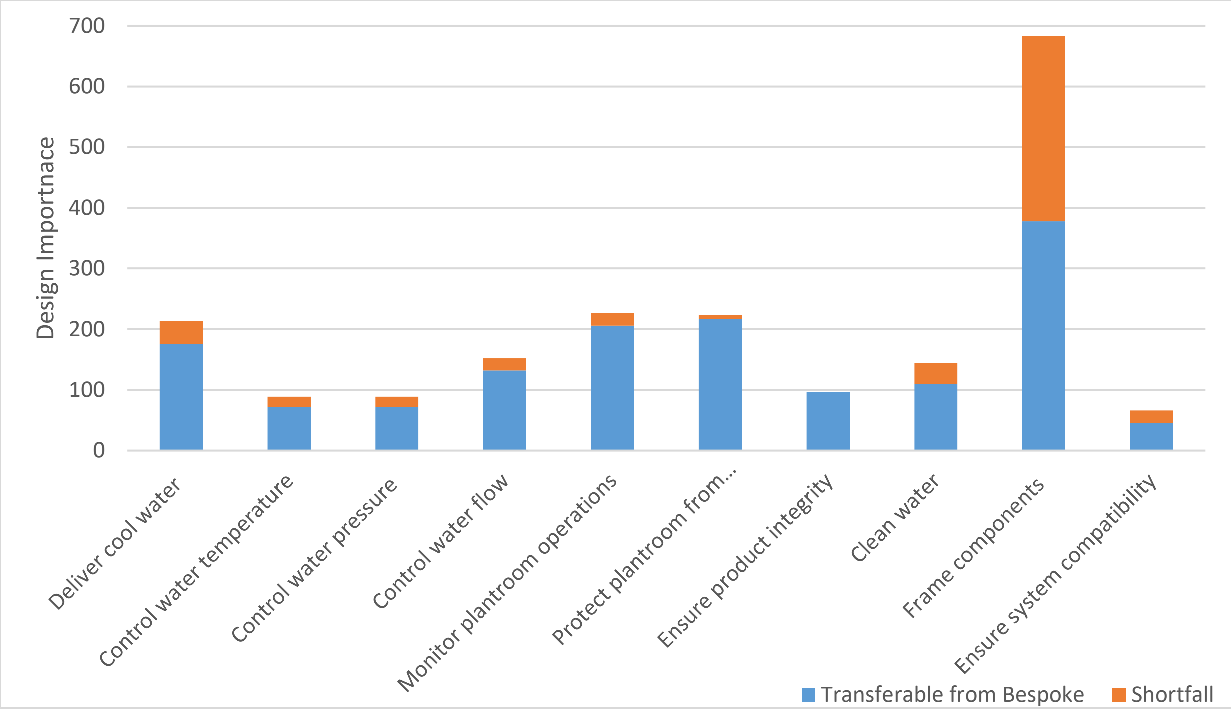


Figure 5.7. Design importance prioritisation analysis of functional requirements

5.4. Results: QFD evaluation

The QFD model was evaluated through a workshop, which included a survey questionnaire.

5.4.1. Survey results

The survey questions covered requirements relevance, accuracy, comprehensiveness as well as aspects of model practicality, support and usefulness (see Figure 5.8). In general, participants showed a high level of agreement with the relevance, accuracy and comprehensiveness of the QFD elements. The accuracy and comprehensiveness of the non-functional requirements deserve a closer attention as various participants either took a neutral position or were in disagreement. Participants in the survey also commented that the QFD model was overly simplified and did not necessarily capture all required aspects. It is important to emphasise that the QFD model was intended to represent requirements at product system level and was not aim at reporting the details of components design. It seems that some participants were expecting to find more information at component level than it was supposed to be in the model.

Participants perceived QFD as a practical tool that offers support for product planning and engineering design. In addition, when comparing the QFD model to the current approach to requirements management used in the collaborating company, participants felt that focusing on a single product with the requirements categories used and the QFD pro-forma is a useful step forward to acquire increased requirements analysis capabilities.

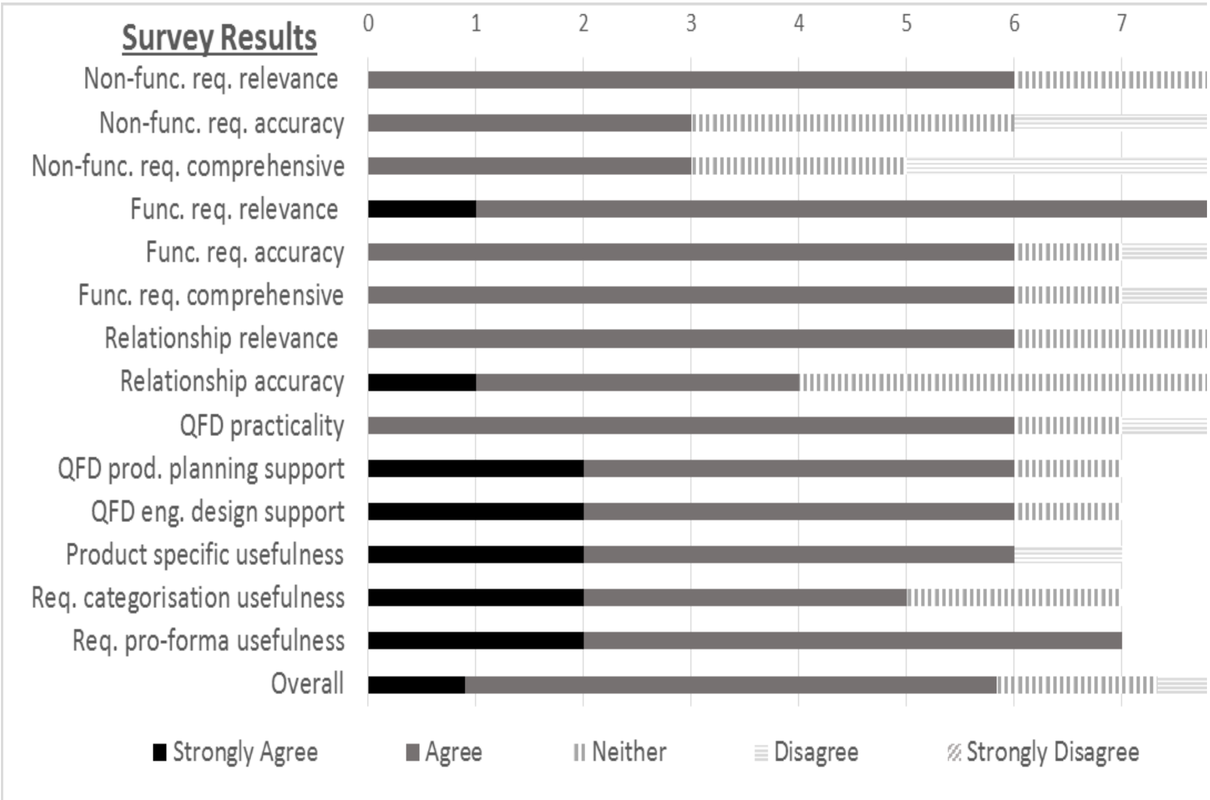


Figure 5.8. QFD workshop survey results

5.4.2. Workshop results

The results of the workshop show that the QFD model is in-line with the business vision of the collaborating company and has the potential to add value to its product development. The QFD tool presents a holistic perspective of the design issues associated with the development of a plantroom product. There was also confirmation that the model offers the benefit of a comprehensive and hierarchical organisation of product requirements. Participants perceived the ability to prioritise product requirements as a beneficial feature of QFD.

The results indicate that adoption of QFD in the construction industry needs to address issues such as increasing the benefits of the tool, integrating it with business operation and reducing barriers to its implementation.

Further QFD features: The QFD model developed so far does not include all known features of the tool. Further development of QFD in construction needs to give careful consideration to business competitive advantages (e.g. cost reduction) and the benefits of automated off-site construction. Hence, future QFD applications have to capture requirements trade-offs and employ the concepts of prioritisation theories, weighting normalisation, and cost drivers.

Integration with business operation: The implementation of QFD would benefit from its integration with existing process guidelines such as the 'Royal Institute of British Architect' design process and V systems engineering process.

Barriers to QFD implementation: Despite the many potential benefits that QFD can bring to the construction industry, there are barriers to its implementation. First, QFD requires the gathering of a comprehensive set of requirements, which may be hard to acquire. For example, this may entail several meetings with stakeholders prior to the development of the QFD matrixes, which is not a simple task in a business environment. There is also an assumption that the client and the respective stakeholders have complete and unchanging knowledge of the requirements, which may not be the case. Second, once the requirements are comprehensively collected there is the issue of interdisciplinary conflicts when organising and prioritising different requirements. Third, there is the risk of resistance to the adoption of the tool, as it conflicts with the traditional culture of flexible operations. In order for the QFD tool to be used successfully in construction, there is a need to increase support for its utilisation.

5.5. Discussion

The current design process (see Chapter 4) suggests that there is room for improvement and that there is a lack of requirements management tools being implemented. The advancement and implementation of requirements management tools in the construction industry is crucially important to achieve modular construction objectives. The utilisation of requirement management tools can support more effective and systematic requirements analysis. This is especially important to facilitate the shift towards modular construction, as requirements management is a key component for better product planning.

The analysis of this chapter underlines that a requirements management tool (i.e QFD) for modular construction needs to have certain aspects to support product planning. They include the possession of the following aspects:

- Systematic characteristic: This would facilitate traceability of requirements and product systems, where traceability maps requirements interdependencies which supports product planning and design.
- Quality information: The information presented in the model needs to be relevant and accurate to facilitate better decision making.
- Prioritisation: Design importance supports the objective of product planning and can be used for prioritisation and indication of actionable activities.
- Visualisation: Matrixes can provide a simple method of visualisation of complex system, which allow an ease of checking the model.
- Compatibility: There is a need for the requirements management tool to be compatible with modularisation tools to support the development of modular product.
- Implementable: Must be practical for industry operations.

This research has gathered positive feedback on the application of QFD to support industrialised construction. While past research works on this topic have also produced results consistent with the results of this research, they were mainly obtained in the context of the current stick-build or basic modular construction (Dikmen et al. 2005; and Gilbert III et al. 2014). Past research works lack specific attributes related to more developed modular construction.

This research has also highlighted other benefits of QFD, which include the following areas:

- Important planning tool. QFD is an important planning tool for introducing new products. With QFD, the final product requirements are pre-established. The tool allows engineering teams to develop technical specifications to match requirements.
- A customer-driven process. QFD is customer or stakeholder oriented tool, which can aid engineers and designers to determine customer's or stakeholder's requirements

prior to the development of technical specifications. The process oriented nature of QFD allows identification of logic holes and to bring together the needs of different stakeholders.

- Improves production efficiency. QFD helps to establish product design and manufacturing standards from as early as during the project concept stage. It facilitates effective development of product specifications and assists in evaluating whether production is proceeding according to plan.

Two key findings of this research are worth highlighting. First, the QFD model developed in this research suggests its usefulness as a functional approach to QFD because of its more rigorous organisation of non-functional and functional requirements, and its documentation of their complex relationships. The QFD model has also shown how to achieve more advanced requirements documentation and analysis capabilities compared to existing approach utilised by the collaborating company. The implementation of a functional approach to QFD and the hierarchical organisation of its elements has led to a more robust and in-depth understanding of requirements. The proposed method of using QFD supports capture of engineering experience, which facilitates the design of next generation products to be less reliant on expert engineers. As compared with past research on QFD in construction, this research develops a more comprehensive model that focused on a live case study. The research as also put more emphasis on the importance of a functional information model to better support modular construction. Second, the prioritisation system is a valuable feature of the QFD model as confirmed by the results of the evaluation workshop. This is because of the tool's ability to identify issues of importance in advanced construction. This feature is crucial for efficient allocation of resources and investments. The application of prioritisation has been in various forms within traditional construction, however its application in modular construction is limited. This research indicates that prioritisation can be used to support an industrial shift towards modular construction.

5.6. Conclusion

This research highlighted the importance of product planning to support industrial shift in the construction sector. It examined the current design process in the collaborating company, which was found to be iterative and expertise dependent. It focussed on compiling client requests and design considerations without considering requirements classification or traceability. The existing process suggests that there is a high potential for the utilisation of systematic requirements management tools to achieve modular construction objective.

This research has also discussed the potential benefits of QFD as a requirements management tool for advanced off-site construction. This was illustrated through a QFD model developed for a modular plantroom. The model supports a more holistic, systematic and structured approach to requirements management as compared with current practices at the collaborating company.

The model also supports a deeper understanding of advanced off-site construction requirements. Specifically, it increases understanding of how non-functional requirements, functional requirements and product systems can be interconnected. It shows how product requirements and product systems can be hierarchically organised. In addition, the model provides the visualisation of advanced off-site consideration especially on issues associated with manufacturing, assembly, design flexibility and transportation.

Another important benefit of the model is its potential to increase efficiency in product planning through the application of the prioritisation mechanism. This can be especially useful for the construction industry to move towards increased industrialisation and advanced off-site construction environment. The prioritisation feature of the QFD model is deemed of high value by experts and specialist engineers who participated in the study, as it can support and direct design efforts in a more efficient manner.

Chapter 6

Hierarchical Quality Function Deployment Model

6.1. Introduction

As construction moves towards more manufacturing like operations, the level of complexity of product development increases. This also increases the requirements of products and operations associated with specialised manufacturing (e.g. modular design and assembly requirements). As complexity grows, engineers working on construction projects need to handle larger volume of information on requirements. To achieve this they require effective methods to handle large-scale requirements challenges. As a result, complexity management tools for the development of construction products becomes more important. The shift from bespoke building to manufacturing operation provides a favourable condition for the adoption of systematic product requirements management methods (Veenstra et al. 2006; Jensen et al. 2014; and Marchesi et al. 2014). However, there is a lack of such tools that support effective management of complex requirements of manufactured building systems.

This chapter discusses requirements management for complex manufactured construction product and builds upon the discussion of Chapter 5. In addition to working on QFD for one product, this research also discusses the implementation of a large set of inter-related QFDs to address multi-dimensional product requirements. In particular, it focuses on complexity management techniques for large modular systems in construction through the application of a Hierarchical Quality Function Deployment (HQFD) model.

While QFD is a more systematic tool compared with other methods for product requirements management in construction (see Chapter 5), it nonetheless suffers from a number of limitations in an environment that involves multi-dimensional factors and multi-layered systems. For instance, although QFD is useful in analysing requirements for construction of a plantroom (e.g. a single component of an apartment building), it has limitation in analysing requirements for construction of an entire apartment building, which involves many different building parts and multi-dimensional elements (e.g. arising from multi-level and multi-segment environment).

The production of a large composite product can be difficult and complicated. In many engineering projects (including construction), there is a heavy reliance on engineering experience to fill technical details and requirements. The application of systematic tools can be an approach to reduce reliance on such experience.

In this regard, the HQFD model proposed in this research offers a systematic tool for requirements analysis of complex construction products (e.g. an entire apartment building). The model can provide a platform to collect expertise information, guidance and help enhanced effectiveness of existing expertise to determine solutions. The model also captures the requirements of a product breakdown and combines QFD with hierarchical analysis to address requirements analysis of complex systems (see Chapter 2). It integrates several layers of QFDs in a network like system taking into account hierarchical considerations and multi-dimensional requirements. It supports analysis of multi-layered requirements for manufactured building systems.

This chapter provides further understanding of large and complex requirements systems and elaborates the key features of HQFD structures, the traceability of requirements and application of data analytics to analyse complex requirements. Following from the explanation of the methodology for the development of the HQFD model, the chapter presents the analysis of the results, discusses lessons learnt and the potential of HQFD model.

6.2. Development of a Hierarchical QFD Model

In the development of the HQFD model, an entire modular apartment building, which represents a complex construction system was examined (see Figures 6.1 and 6.2). The model comprises a network of QFD models of related products (i.e. building segments), which involve different levels of requirements. The HQFD model was developed in collaboration with and validated by engineers from the collaborating company.

Figure 6.1. A generic apartment building (Source: Laing O'Rourke)

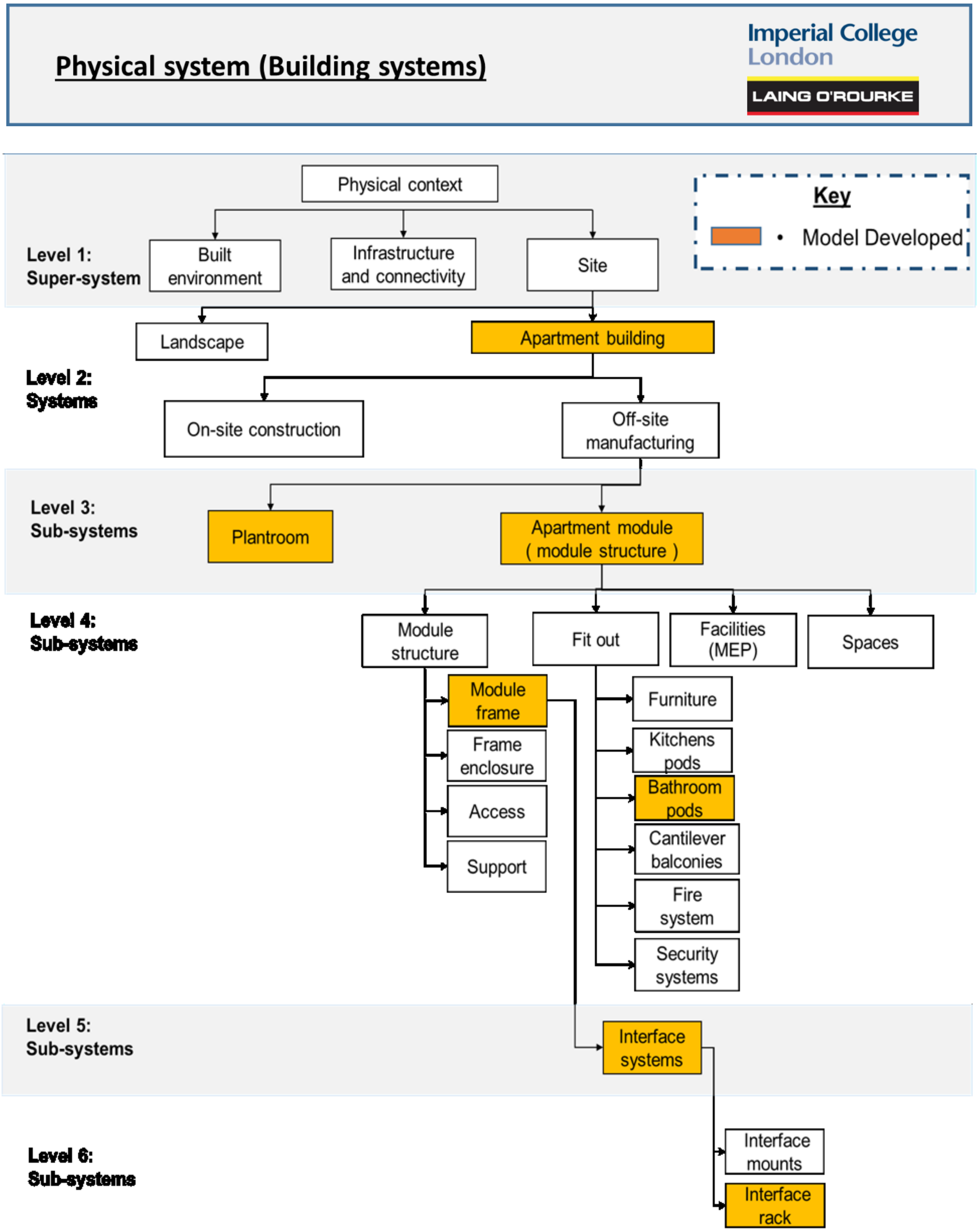


Figure 6.2. Hierarchical tree for physical building system (product breakdown)

A number of methods were used to collect data from the collaborating company and analyse them (see Figure 6.3).

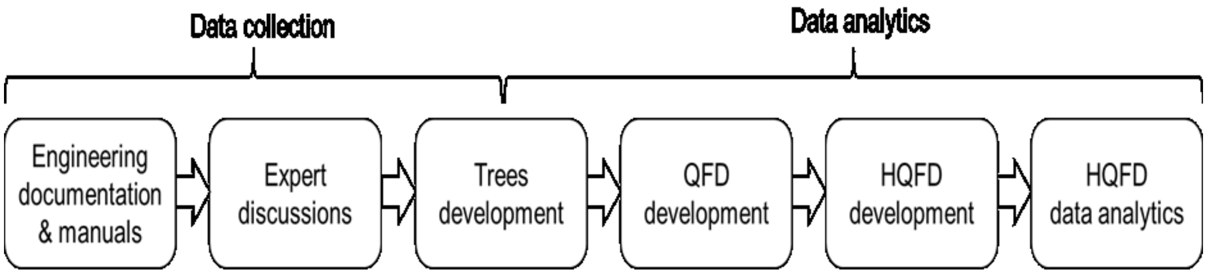


Figure 6.3. Data collection and analysis methods

A total of 6 QFD models, which consisted of 11 QFD matrixes were developed based on a reverse engineering approach. The approach involved examination of information on product and design requirements, which were extracted from technical documents and interviews with engineers at the collaborating company. Other methods used for the collection of information included matrix development, weighting and data analytics application.

6.2.1. Data collection

The data collection methods are listed below:

iii) **Examination of existing documentation:** An extensive review of documents centred on modular construction design was conducted at the collaborating company to understand the various product features and design decisions made by the company. The information collected was used to identify requirements. The documents reviewed include CAD files, schematics, bills of materials, product manuals and requirements documentation. This data collection process is similar to that explained in Chapter 5.

iv) **Reverse engineering for the collection of product design data:** Reverse engineering was used for data collection in this research. It involved examination of existing product documentation on a prototype modular building design, and discussion with engineers from the collaborating company to identify requirements. The topics investigated cover design processes, product objectives and product technical issues.

v) **Extraction of requirements information from engineers:** Several interviews and discussions with engineers at the collaborating company were conducted to obtain information on design process, product requirements and design rational. These interviews and discussions were also used to clarify and validate understanding of the information collected. The information was used to support the development and validation of requirement trees and QFD models.

6.2.2. Data analysis

Tree development: The knowledge gained from the examination of documentations and discussion was translated into requirement trees and reviewed with the collaborating company's engineers. Three types of trees (i.e. non-functional requirement, functional requirements and products systems) were developed following the information model proposed by Burge (2007). A total of 12 trees were developed to break down the requirements and product of six segments covered in this research.

These trees cover the various product levels, requirements domain and product segments that make up the HQFD model. The product segments include "modular apartment building", "apartment module", "module frame", "interface systems", "interface rack", and "bathroom pods". For each product segment, a non-functional requirement tree, functional requirements tree and product systems tree was developed (see Figure 6.4). Appendix 3 presents the classification of the three types of trees.

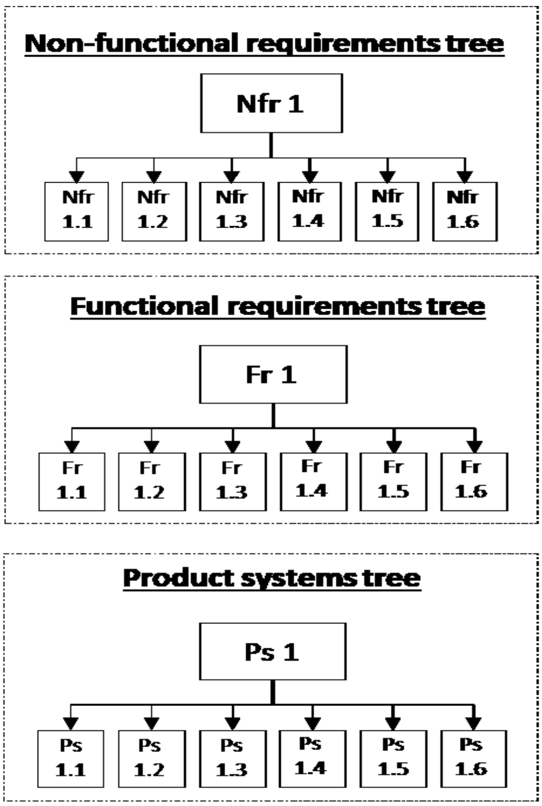


Figure 6.4. Non-functional, functional and product systems trees

These trees were generated based on “bottom up” and “top down” reverse engineering to facilitate collection of a comprehensive set of requirements. The requirements were then organised into categories, which included stakeholder’s perspectives and product levels.

QFD development: The information used to produce the hierarchical trees was then applied for the development of QFD models (see Figure 6.5). A total of 11 matrixes for 6 product segments across 4 of 6 product levels were developed. These matrixes are introduced in Section 6.3.

The developed QFD models collectively form the HQFD system, which covers a modular apartment building consisting of six product levels from site level at level 1 to component level at level 6. The system also captures all subcontracted products (e.g. module frames, bathroom pods and apartment modules).

QFD matrix structure: Understanding the QFD matrix structure is important to determine how product information is presented in the HQFD model. The significance of the QFD matrix structure and the implementation of the QFD have already been explained in Chapter 5 (see Sections 5.2 and 5.3). The information model for the QFD matrix structure is based on that of Burge (2007).

QFD relationship weightings: The weightings implemented in this chapter are different to that explained in Chapter 5, in terms of different sets of definitions and values. Weightings are part of the developed QFD models. Weightings show the strength of interdependencies between various requirements. Each QFD model consists of two QFD matrixes (QFD 1 and QFD 2). Both matrixes have requirements relationship weightings on a scale of 1, 3 and 9 (where 1 reflects low relationship and 9 strong relationship). Such information can facilitate a better understanding of the interrelationships of requirements across the HQFD system. They are also invaluable for further data analytics application.

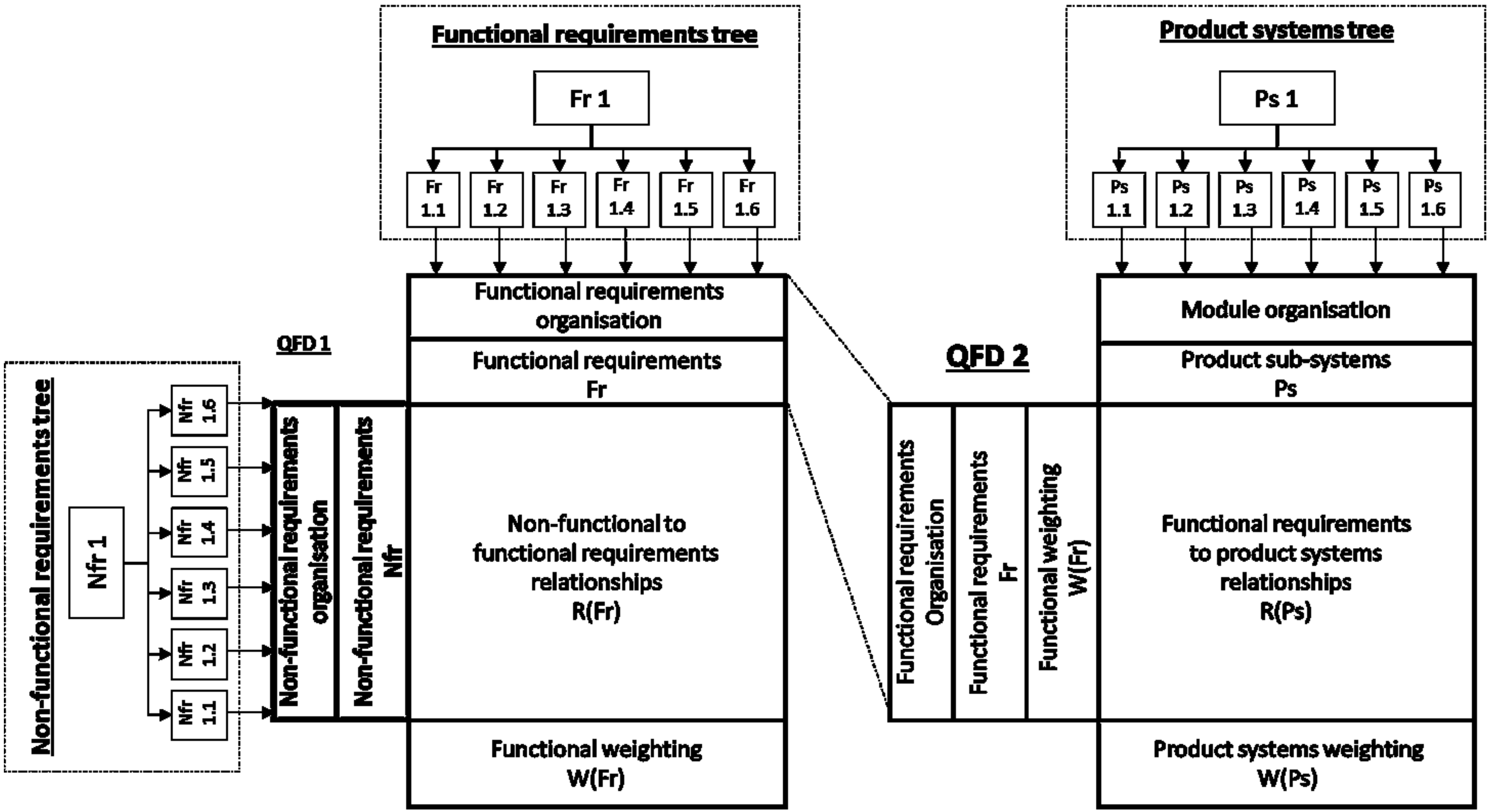


Figure 6.5. Trees relationships to QFD

Relationship weightings for QFD 1: Non-functional requirements relate to product requirements that are not specific to a product functional system (e.g. customer requirements) and functional requirement involves product requirements that are specific to a product functional system.

The relationship weighting indicators for QFD 1 are interpreted as below:

- 9 = Direct influence. Design consideration is an essential/priority to satisfy the specific non-functional requirement.
- 3 = Direct influence. Design consideration is beneficial to satisfying the specific non-functional requirement. Design consideration must be made but it is not a priority.
- 1 = Indirect influence. Design consideration is beneficial but will not prevent the satisfaction of the specific non-functional requirement if not met.

Relationship weightings for QFD 2: Functional requirement relates to product requirements that are specific to a product functional system, and product system covers the technical solution or components.

The relationship weighting indicators for QFD 2 are interpreted as below:

- 9 = A technical solution that is a main solution for a functional requirement.
- 3 = A technical solution that is a partial or secondary solution for a functional requirement.
- 1 = A technical solution that plays a supporting role for the fulfilment of a functional requirement.

Index and weighting calculation: In order to determine the accumulated weighting (i.e. design emphasis, see Chapter 5) of a requirement or product system, the associate requirement relationship weighting needs to be added. This accumulated weighting serves as a measurement for product design importance.

The weighting of QFD functional requirements and product sub-systems was calculated as per each equation below (same as Chapter 5): where W(Fr)x (the calculated weighting of each 'functional requirement') is determined by the product-sum of all associated non-functional requirements and their respective requirement weightings, and where W(Ps)y (the calculated weighting of each 'product sub-system') is determined by the sum-product of all associated functional requirements and their respective requirement weighting.

$$\mathrm{W(Fr)}_x = \sum(\mathrm{R(Fr)}_{xy}) \quad (1)$$

$$W(Ps)_y = \sum(W(Fr)_z \times R(Ps)_{yz}) \quad (2)$$

$\mathrm{W(Fr)}_x$ is the calculated weighing for the 'functional requirement' with reference number x. $\mathrm{W(Nfr)}_y$ is the assigned weighing of 'non-functional requirement' with reference number x. $\mathrm{R(Fr)}_{xy}$ is the weighting of a relationship associated with that specific functional requirement on the xy intesect. x is the reference number of a non-functional requirement sitting on the QFD1 x axis. $W(Ps)_y$ is the calculated weighting for the 'product sub-system' with reference number y. $R(Ps)_{yz}$ is the weighting of relationship associated with that specific product sub-system on that yz intersect. y is the reference number of a functional requirement sitting on the QFD1 y axis or QFD2 x axis. z is the reference number of a product sub-system siting on the QFD2 x axis.

Dimensions of the hierarchical model: the modelling of the requirements for a complex product such as an apartment building was undertaken based on three main dimensions, namely, product segment, design domain and product level (see Figure 6.6).

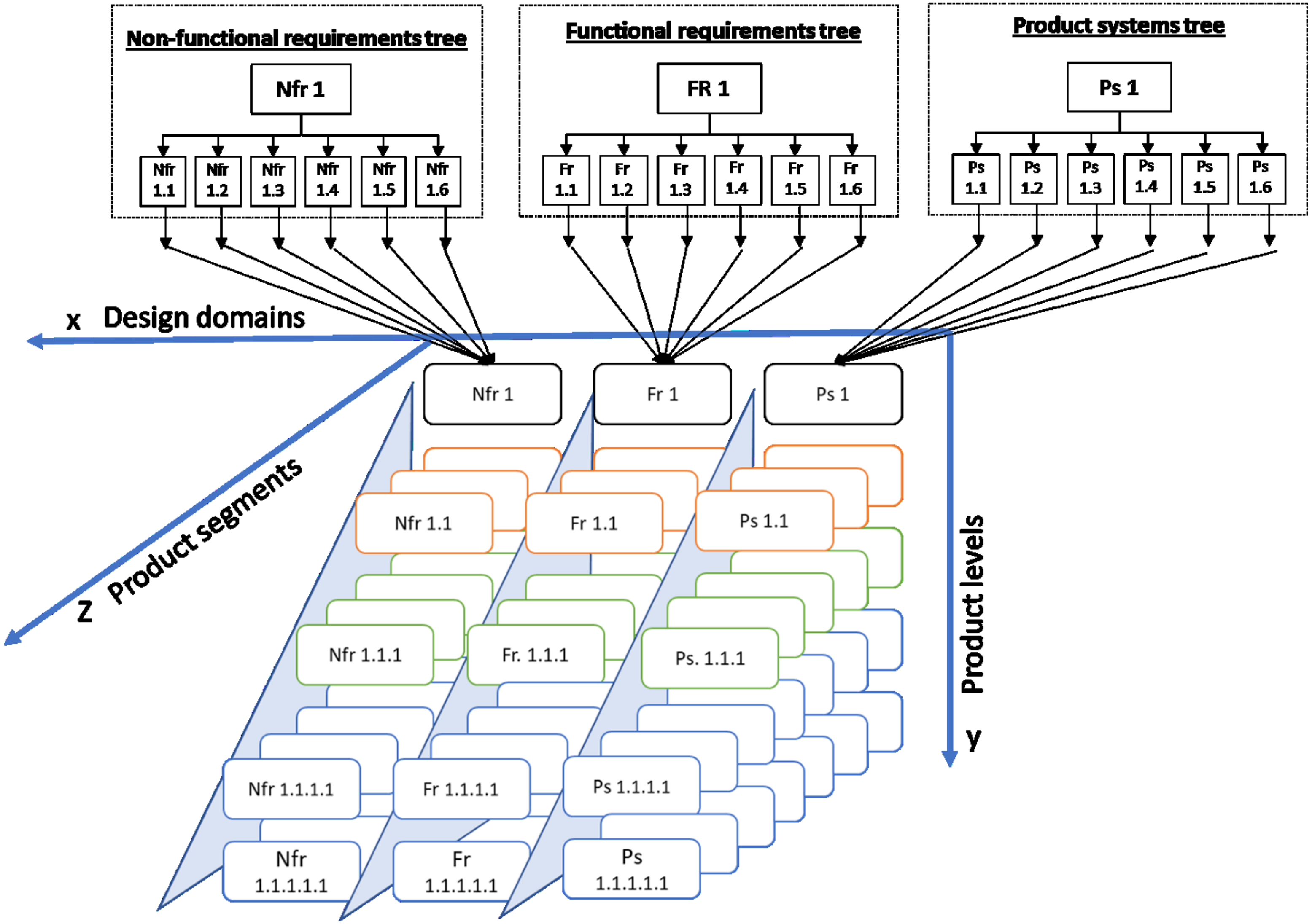


Figure 6.6. Three dimensions for hierarchical modelling

The first dimension is the product segment, which refers to a portion of the overall building at a specific product level (e.g. level 3 illustrated in Figure 6.7, and for a more detailed version see appendix 3). These segments include building structure, building fit-out, public spaces, MEP, interface system, plantrooms, and apartment modules.

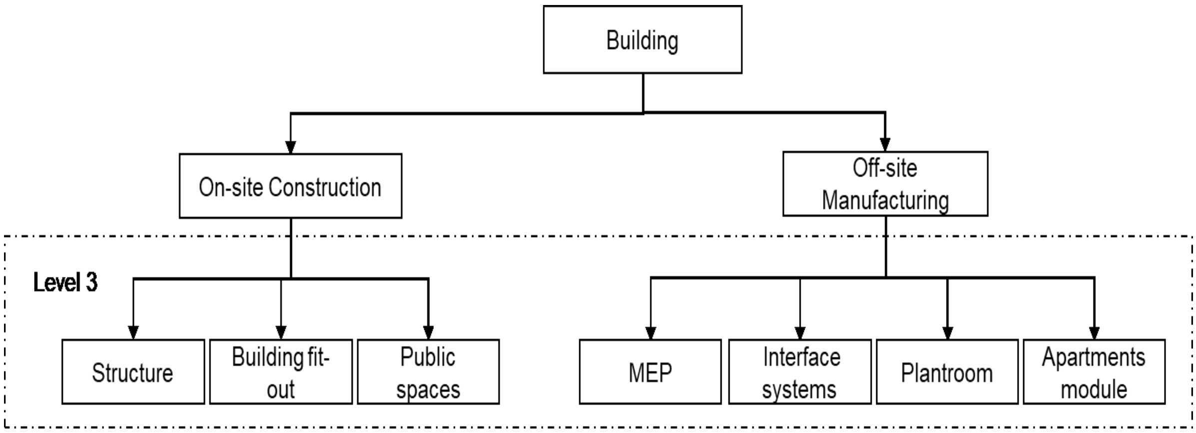


Figure 6.7. Products segments on level 3

The second dimension is the design domain which refers to three main types of information: non-functional requirements (NFR), functional requirements (FR) and product sub-systems (PS). This set of information was selected because it supports modular product development. Non-functional requirements are whole system characteristics of the product, functional requirements are demands on product functionality, and product sub-systems are component systems that form the architecture of the product (Burge 2007).

The third dimension is the product level, which cover i) apartment building, ii) module apartment, iii) the module frame, iv) interfacing systems, and v) alignment rack (see Figure 6.8).

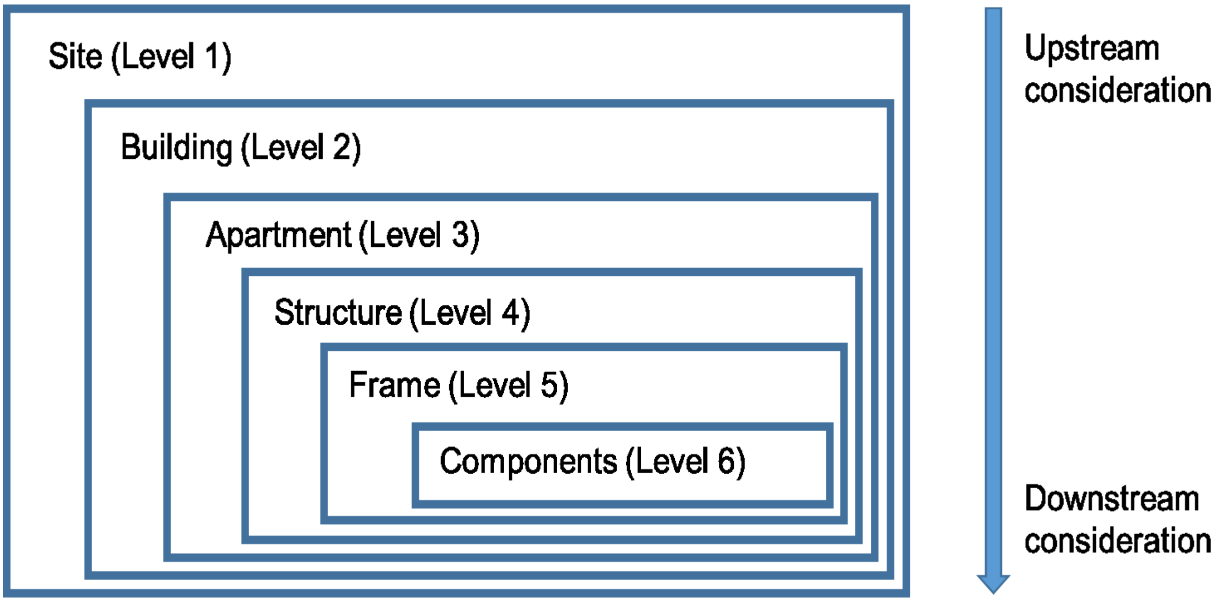


Figure 6.8. Product levels

HQFD development: Building on the dimensions introduced previously, a hierarchical QFD model was implemented to manage and analyse complex requirements (see Figure 6.9). QFD was implemented in a hierarchical structure, where several QFDs form a larger Hierarchical QFD model, which is referred to as HQFD in this research. The model allows to break down the requirements for a large complex product into segments, design domains and product layers.

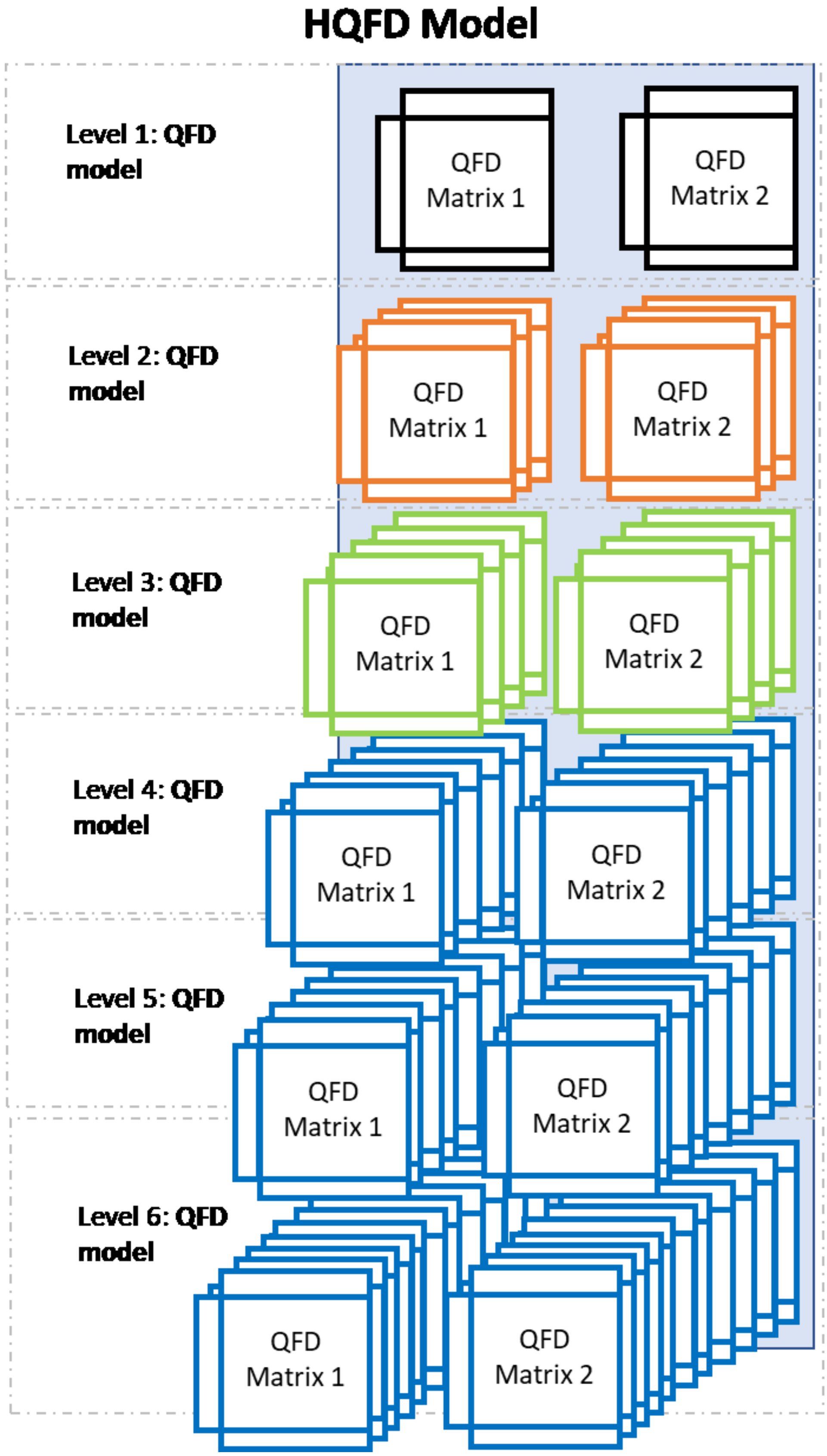


Figure 6.9. Structure of a HQFD model

Model validation: The models investigated in the research were developed with support from the collaborating company's engineers through regular discussions, meetings and email correspondences. The meetings and discussions facilitated the collection of data on products development and requirements, product breakdown trees, development of QFD models, and validation of trees and QFD models. The expert engineers include highly experienced personnel who work on the development of modular construction at the collaborating company. They were two systems engineers, one civil engineer, two architects, and one structural engineer. The data collected were reviewed to understand product functionality, product features, design rationale and the design procedure. Discussions with the engineers play an important role in the collection of information at various stages of the research process and in the validation of the trees and QFD models.

HQFD data analytics application: HQFD data analytics in this chapter refers to the analysis of the QFD and HQFD models based on weightings generated in this research. This is to attain additional insight into manufactured construction products and to indicate important product features needed for developing effective products. An example of data analytics associated with the HQFD model was conducted on a modular apartment building, which involves 3 product segments (i.e. apartment module, module frame, and bathroom pods). The data analytics example illustrated the potential impacts that an industrial shift from bespoke construction to manufactured construction have on the requirements of a building system. Analyses for each of the QFD sets were also conducted. The data analytics application was based on weighting values (non-function requirement weighting W(Nfr), functional requirement weighting W(Fr) and product systems weightings W(Ps)). W(Fr) and W(Ps) were calculated from equations 1 and 2. The calculations for W(Nfr) can be seen in equation 3.

$$W(Nfr) = \sum(W(Fr) \times \sum W(Ps)) \quad (3)$$

In order to attain an indicator of the impact that an industrial shift (towards advanced manufacturing and modular design) might have on requirements, certain "Nfr" was grouped as "transferable from bespoke" (Bespoke), "advance manufacturing and modular design specific" (AM&MD 1), and "advance manufacturing and modular design influenced" (AM&MD 2). Elements of Nfr were clustered by separating the weights of three Nfr groups based on production origination. The Nfr groups and their corresponding elements are described below:

i) Bespoke transferable (Bespoke) is made up of Nfr categories such as living, comfort, safety, security, maintainability, design, quality and sustainability. For example, an apartment building needs to provide "comfort" to its inhabitants, and providing this comfort is independent to the method of production of the building.

ii) Advance manufacturing and modular design specific (AM&MD1) consisted of Nfr categories (e.g. configurability, design flexibility, manufacturing, assembly and transportation). For example, an apartment building design flexibility is highly related to modular design.

iii) Two Nfr categories (safety and design) can also be "influenced" by advance manufacturing and modular design (AM&MD 2). For example, at an apartment module level, safety and design considerations need to be revaluated to conform to AM&MD form of construction.

6.3. Results

The HQFD model developed in this research supports requirements management of complex construction products through the following features:

i) Management of complex product requirements by building a hierarchy of QFD matrixes.

ii) Traceability of complex product requirements by capturing requirements dependencies and mapping requirements relationships.

iii) Extraction of design insights by performing data analytics.

The above three features are further explained in the following sections.

6.3.1. HQFD structure for complexity management

The HQFD model allows the breakdown of a complex system into a network of QFDs to support requirements analysis. Table 6.1 lists the QFD models that were developed and the corresponding figures, which illustrate how complex requirements information are structured through the network of QFDs. The QFD models cover QFD1 and QFD2 matrixes for 6 segments of the buildings systems (i.e. apartment building, apartment module, module frame, interface systems, interface rack and bathroom pods).

Table 6.1. List of QFDs

Product level	QFD 1	QFD 2	Number of requirements
Apartment building (level 2)	Figure 6.10 (Part 1) Figure 6.11 (Part 2)	Figure 6.12	Nfr = 55 Fr = 30 Ps = 30
Apartment module (level 3)	Figure 6.13 (Part 1) Figure 6.14 (Part 2)	Figure 6.15	Nfr =41 Fr =25 Ps =15
Module frame (level 4)	Figure 6.16	Figure 6.17	Nfr = 23 Fr = 24 Ps = 7
Interfacing systems (level 5)	Figure 6.18	Figure 6.19	Nfr = 20 Fr = 12 Ps = 2
Interface rack (level 6)	Figure 6.20	N.A.	Nfr = 14 Fr = 11 Ps = 1
Bathroom pods (level 4)	Figure 6.21 (Part 1) Figure 6.22 (Part 2)	Figure 6.23 (Part 1) Figure 6.24 (Part 2)	Nfr = 35 Fr = 22 Ps = 49

Notes: Nfr = Non-functional requirements; Fr = Functional requirements; Ps = Product systems.

Provision of a good information structure is important to support management of complex systems and to provide a platform to conduct further data analysis. The HQFD model applies the multi-dimensional information (i.e. product segment, design domain and product level, see Figure 6.6) described in Section 6.2.2. Through the multi-dimensional information model, the HQFD model has provided a structure that supports the breakdown of design domains (i.e. non-functional requirements, functional requirements and product systems) of an apartment building across product levels and segments (see Figures 6.2 and 6.6). Such breakdown of information, QFD matrixes structure and HQFD network system enable a more effective analysis and management of complex requirements.

Apartment building QFD 1				Facilitate living													Ensure structural integrity					Integrate auxiliary		Protect systems									
				Provide access and navigation		House people							Deliver services				Ensure structural integrity					Park vehicles	Entertain inhabitant	Protect systems from environment					Protect systems from threats				
				In / out take people	Welcome and direct people	Provide access	Facilitate day living	Facilitate dining	Facilitate resting	Facilitate personal hygiene	Facilitate space /room connection	Provide outdoor space	Provide a comfortable enviroment	Run services	Control services	Dispose waste	Modular structural integrity	Ensure alignment	Loading integrity	Structural foundation integrity	Enclose building	Park vehicles	Facilitate social living and entertainment	Protect from wind	Protect from extreme temperatures	Protect from lighting	Protect from rain	Protect from earthquake	Secure entrance	Monitor people traffic	Provide fire safety	Provide locking mechanisms	Acoustic
Inhabitant	Habitation and comfort	Living	Ease of access	9	1	9																											
			Adequate space				9	9	9	9	9	9																					
			Pleasant internal environment				9	9	9	9	9	9	9																				9
		Comfort	Satisfactory illumination				3	3	3	3	3	3	9	9	9																		
			Comfortable temperature										9	9																			
			Good quality air										9	9																			
			Ease of services access											9																			
		Safety	Fast evacuation	3	3	3																										3	
			Low number of safety hazards	1	1	3	1	1	1	1	1	1	9	9	3											9	9	9			9	1	
		Security	Minimise number of intrusions	9		9																							9	9		9	
Building Management	Building Management	Maintainability	Low number of repairs	3	3	3	3	3	3	3	3	3																					
			Fast cleaning and maintaining	3	3	3	3	3	3	3	3	3																					
			Low running cost	1	1	1	1	1	1	1	1	1																					
Client	Project	Design	Aesthetically pleasing	3	9	3	9	9	9	9	9	9						9			9												
			Large number of dimensions and layout options			1	9	9	9	9	9	9																					
			Gross floor area		1		9	9	9	9	9	9									9												
			Low cost	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	
			Low number of finishing flaws	9	9	9	9	9	9	9	9	9					3	3	3	3	3	9	9									9	
Architecture company	Building	Quality / Assurance	Materials	9	9	9	9	9	9	9	9	9	9	9		9	9	9	9	9	9	9	9										3
			Corrosion protection			9	9	9	9	9	9	9	9	9		9	9	9	9	9	9	9		9			9						
			No/low air leakage																		9			9									1
			No/Low liquid leakage							3			9	9							9												
			Reduce acoustic leakage				9	9	9	9	9		9	9			9				9												9
			Reduce thermal leakage				3	3	3	3	3										9				9								
			Protect from rain & wind forces																					9	9	9	9						
			Robust			3	3	3	3	3	3	3		3	3	3	9	9	9	9	9	9											
		Sustainability	Low number of building malfunctions											9	9	9	9	9				1							9	9		9	
			Long lasting components	9	9	1	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9								9	9	9	
			Energy consumption				9	9	9	9				9	9						9		9										
			Low carbon footprint	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
			Recyclability	1			1	1	1	1	1	1	1	1		3	1		1		1												

Figure 6.10. Apartment building QFD 1 (Part 1)

Apartment building QFD 1				Facilitate living													Ensure structural integrity					Integrate auxiliary		Protect systems									
				Provide access and navigation		House people								Deliver services			Ensure structural integrity					Park vehicles	Entertain inhabitant	Protect systems from environment					Protect systems from threats				
				In / out take people	Welcome and direct people	Provide access	Facilitate day living	Facilitate dining	Facilitate resting	Facilitate personal hygiene	Facilitate space /room connection	Provide outdoor space	Provide a comfortable enviroment	Run services	Control services	Dispose waste	Modular structural integrity	Ensure alignment	Loading integrity	Structural foundation integrity	Enclose building	Park vehicles	Facilitate social living and entertainment	Protect from wind	Protect from extreme temperatures	Protect from lighting	Protect from rain	Protect from earthquake	Secure entrance	Monitor people traffic	Provide fire safety	Provide locking mechanisms	Acoustic
Contruction company	Product	Configurability	Large number of living options				9							9																			
			Large number of dining options					9						9																			
			Large number of sanitary options							9				9																			
			Large number of cooking options					9						9																			
			Large number of resting options						9					9																			
		Design flexibility	Upgrade flexibility				9	9	9	9	9	9		9	9		9	9															
			Configurability				9	9	9	9	9	9		9			9	9															
			Adjustable elements		9		9	9	9	9	9	9		9			9	9															
	Production	Manufacturing /Assembly (off-site)	Ease of manufacturing			9	9	9	9	9	9	9		9			9	9															
			Ease of assembly			9	9	9	9	9	9	9		9			9	9															
			High standardisation level			9	9	9	9	9	9	9		9			9	9															
			Ease of quality control			9	9	9	9	9	9	9		9			9	9															
			High speed of assembly			9	9	9	9	9	9	9		9			9	9															
			Low cost and predicable supply chain			9	9	9	9	9	9	9		9			9	9															
			Safe assembly			9	9	9	9	9	9	9		9			9	9															
		Assembly (on-site)	Ease of assembly			9	9	9	9	9	9	9		9			9	9															
			Small clearance														9	9															
			Strength of connection														9	9															
			Ease of installation														3	9															
			Safe assembly														3	9															
		Transportability	Transportable size														3	1															
			Reduce transportation damage														3	1															
			Fast transportation lifting ability														3	1															
			Transportability and lifting capability														3	1															
				70	68	148	235	244	235	238	217	205	101	266	61	52	203	206	50	49	113	56	37	37	28	28	37	19	28	37	28	50	23

Figure 6.11. Apartment building QFD 1 (Part 2)

		Apartment building QFD 2	Structure					Building fit-out			Public spaces				MEP									Interface systems		Apartment					
			Core	Flanges	Bespoke	Enclosure	Parking	Rain control system	Security systems	Fire system	Corridor	Lobby	Stairway	Lifts	Small power and lighting	Low voltage	Smart sensors and control	Hot and cold water services	Foul drainage	Heating system	Ventilation & moisture control	Sprinkler system	Service cabin	Joints	Holding	Plantroom	Balcony	Structure	Facilities	Fit out	Spaces
Facilitate living	Provide access and navigation	In / out take people										9																			
		Welcome and direct people									9	9	9	9																	
	House people	Provide access																								1	9	9		1	9
		Facilitate day living													3	3	1	3	3	9	3		3			1		3	9	9	9
		Facilitate dining														9		9			9					1		3	9	9	9
		Facilitate resting													9	9				9	3					1		3	9	9	9
		Facilitate personal hygiene																9								1		3	9	9	9
		Facilitate space /room connection																						1	1			9	3	3	3
		Provide outdoor space																			1						9	3			
		Provide a comfortable enviroment																									9	1	9	9	9
	Deliver services	Run services													9	9	9	9	9	9	9	9	9			9			9		
		Control services													3	3	3	3	3	3	3	3	9			9			9		
		Dispose waste																	9							9			9		
Ensure structural integrity	Ensure structural integrity	Modular structural integrity	9	9		3																		9	9		9				
		Ensure alignment	3	3		3																		9	9		1				
		Loading integrity	9	9		3																		9	9		9				
		Structural foundation integrity					1																								
		Enclose building		3	1	9																		9	9		1				
Integrate auxiliary	Park vehicles	Park vehicles					9																								
	Entertain inhabitant	Facilitate social living and entertainment										3															1		9	9	9
Protect systems	Protect systems from environment	Protect from wind			1	9		3																			1				
		Protect from extreme temperatures			1	9	1																								
		Protect from lighting			1	9		3																			1				
		Protect from rain			1	9	3	9																			3				
		Protect from earthquake	9	9	1	3		1																			1				
	Protect systems from threats	Secure entrance							9																						
		Monitor people traffic							9																						
		Provide fire safety								9																					
		Provide locking mechanisms							9																						
		Acoustic		3		3					3	3	3	3				1	1	1	1			1	1	3	3	3	3	3	3
			3390	3798	262	3852	692	547	1035	252	762	1503	762	762	6504	9105	3523	9155	4556	8153	7734	3252	4485	5901	5901	5462	7496	7709	16128	12136	13320

Figure 6.12. Apartment building QFD 2

Apartment module QFD 1		House people							Ensure structural integrity				Facilitate services								Protect from environment, threats and disturbances				Enable safe and effective transportation	
		Provide access	Facilitate day living	Facilitate dining	Facilitate resting	Facilitate personal hygiene	Facilitate space/room connection	Provide outdoor spaces	Modular structural integrity	Enclose room	Utilities structural support	Modular structural alignment	Deliver water	Run lighting	Deliver electricity	Run heating	Extract bad air	Control services	Dispose waste	TV, Internet	Protect from water damage	Protect from electrical damage	Protect from wind damage	Protect from fire	Support handling	Mount supporting structure
Design	Cost	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Low number of finishing flaws	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Large number of layout options	9	9	9	9	9	9	9	3	3	3	3														
	Waterproofing and vapour resistance												9	9		9		9	9		9					
	Strength and rigidity								9	9	9	9														
	Light weight	9	9	9	9	9	9	9	9	9	9	9														
	Dimensions restriction	9	9	9	9	9	9	9	9	9	9	9														
Living	Ease of access	9	3	3	3	3	3	3	3	3	3	3														
	Pleasant internal environment	9	9	9	9	9	9	9													3	3	3	3		
Safety	Low number of safety hazards	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	9	9
	Protect from intrusion	9						3		9																
Comfort	Satisfactory lighting													9				9								
	Comfortable temperate															9		9								
	Good quality air																9									
	Ease of service access																	3								
Quality/Assurance	Corrosion protection	3	3	3	3	3	3	3	3	3	3	3	9	3	3	3	3	3	3	3	9	3	9	3		
	No/Low air leakage	9								9																
	Reduce acoustic leakage	9							9	9	9	9	9	3	3	3	9	9	9							
	Reduce thermal leakage protect	9							9	9	9	9	9	3	3	3	9	9	9							
	Protect from rain & wind forces	9							9	9		9											9			
	Performance retention	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9

Figure 6.13. Apartment module QFD 1 (Part 1)

Apartment module QFD 1		House people							Ensure structural integrity				Facilitate services								Protect from environment, threats and disturbances				Enable safe and effective transportation	
		Provide access	Facilitate day living	Facilitate dining	Facilitate resting	Facilitate personal hygiene	Facilitate space/room connection	Provide outdoor spaces	Modular structural integrity	Enclose room	Utilities structural support	Modular structural alignment	Deliver water	Run lighting	Deliver electricity	Run heating	Extract bad air	Control services	Dispose waste	TV, Internet	Protect from water damage	Protect from electrical damage	Protect from wind damage	Protect from fire	Support handling	Mount supporting structure
Maintainability	Fast cleaning and maintaining	9	9	9	9	9	9	9					9	9	9	9	9	9	9	9						
Sustainability	Long lasting components	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9		9
	Energy consumption									9			9	9	9	9	9	9	9	9						
Design Flexibility	Upgrade flexibility	1	1	1	1	1	1	1	9	9	1	9														9
	Configurability	9	9	9	9	9	9	9	9	9	9	9														9
	Flexible layout	9	9	9	9	9	9	9																		
	Support add-ons								9	3		9														9
Manufacturing / Assembly (off-site)	Ease & accuracy of manufacturing	3	3	3	3	3	3	3	9	9	9	9	3	3	3	3	3	3	3	3	3				9	9
	Ease & accuracy of assembly	3	3	3	3	3	3	3	9	9	9	9	3	3	3	3	3	3	3	3	3				9	9
	High standardisation level	3	3	3	3	3	3	3	9	9	9	9	3	3	3	3	3	3	3	3	3				9	9
	Ease of quality control	3	3	3	3	3	3	3	9	9	9	9	3	3	3	3	3	3	3	3	3				9	9
	Low cost and predictable	3	3	3	3	3	3	3	9	9	9	9	3	3	3	3	3	3	3	3	3				9	9
Assembly (on-site)	Accuracy of assembly								9	1		9													9	9
	Strength of assembly								9			9														9
	Ease of instalment and alignment								9	1		9													9	9
	Ease of system integration											9	9	9	9	9	9	9	9	9						9
	Stacking ability								9			9														9
Transportability	Transportable size		9	9	9	9	9	9	9																	
	Reduces transportation damage									3															9	
	Fast transpiration lifting ability									3															9	
		163	121	121	121	121	121	124	207	191	136	207	105	96	78	96	99	120	99	72	63	33	48	33	105	150

Figure 6.14. Apartment module QFD 1 (Part 2)

Apartment module QFD 2		Structure				Facilities				Fit out				Spaces		
		Frame	Frame enclosure	Access	Support	Plumbing	Heating	Ventilation and moisture control	Electrical	Furniture	Kitchen pod	Bathroom pod	Cantilever balconies	Corridor	Sleeping space	Living space
House people	Provide access	1	9	9												
	Facilitate day living															9
	Facilitate dining										9					9
	Facilitate resting														9	
	Facilitate personal hygiene											9				
	Facilitate space/room connection													9		
	Provide outdoor spaces												9			
Ensure structural Integrity	Modular structural integrity	9	9													
	Enclose room	3	9													
	Utilities structural support			9	9											
	Modular structural alignment	3														
Facilitate services	Deliver water					9										
	Run lighting								9							
	Deliver electricity								9							
	Run heating						9									
	Extract bad air							9								
	Control services								9							
	Dispose waste					9					9	9				
	TV, Internet								9							
Protect from environment, threats and disturbances	protect from water damage	1	9	9		9			9		9	9	9			
	Protect from electrical damage							9	9		9	9	9			
	Protect from wind damage	3	9													
	Protect from fire	9	9	9	9	9				3	3	3		9	9	9
Enable safe and effective transportation	Support handling	9	9		9					9	9					
	Mount supporting structure	9	9		9											
		47	72	36	36	36	9	18	54	12	48	39	27	18	18	27

Figure 6.15. Apartment module QFD 2

Module frame QFD 1			Ensure structural integrity			Ensure structural functionality	Support geometric flexibility				Interface		Protect systems			Transportation aid
			Module structural integrity	Support internal mounts	Support utilities structurally	Define room envelope	Upgrade flexibility	Configurability	Flexible layout	Support add-ons	Align module	Allow mounting add-on	Protect from water damage	Protect from wind damage	Protect from fire damage	Lifting ability
Design	Cost	£	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Low number of finishing flaws		9	9	9	9	3	3	3	3	9	9				
	Strength and rigidity	N or Nm	9	9	9	9	9	9	9	9	9	9				
	Light weight	Kg	9	9	9	1	1	1	1	1	1	1				
	Dimension restrictions	Hight internal: 2.5 - 2.6m	9	9	9	3										
Safety	Low number of safety hazards		9	9	9	9	9	9	9	9	9	9				
Quality / Assurance	Corrosion protection										9	9	9	9	9	
	Reduce Acoustic Leakage		9		9	9					9					
	Reduce Thermal Leakage		9		9	9					9					
	Protect from rain & wind forces		9		9	9					9	9				
	Performance retention		9	9	9	9					9	9				
Sustainability	Long lasting components	60 Years	9	9	9	9					9	9	9	9	9	
Manufacturing (off-site)	Ease & accuracy of manufacturing		9	9	9	9	9	9	9	9	9	9				
	Ease & accuracy of assembly		9	9	9	9	9	9	9	9	9	9				
	High standardisation level		9	9	9	9	9	9	9	9	9	9				
	Ease of quality control		9	9	9	9	9	9	9	9	9	9				
	Low cost and predictable supply chain		9	9	9	9	9	9	9	9	9	9				
Assembly (on-site)	Accuracy of assembly	0.5mm	9								9	9				9
	Strength of connection										9	9				
	Ease of installation, alignment and intergation				9						9	9				
	Stacking ability		9	9	9	3					9					
Transportability	Transportable size		9	9	9											
	Reduce transportation damage															9
			165	129	165	127	70	70	70	70	166	139	21	21	21	21

Figure 6.16. Module frame QFD 1

Module frame QFD 2		Interface systems	Top	Bottom	Long side 1	Long side 2	Short side 1	Short side 2
Ensure structural integrity	Module structural integrity (internal and external loads)	9	9	9	9	9	9	9
	Support internal mounts	9	9	9	9	9	9	9
	Support utilities structurally		9	9	9	9	9	9
Ensure structural functionality	Define room envelope		9	9	9	9	9	9
Support geometric flexibility	Upgrade flexibility	9						
	Configurability	3						
	Flexible layout	3	3	3	3	3	3	3
	Support add-ons	9						
Interface	Align module	9						
	Allow mounting add-on (balcony and additional spaces)	9	3	3	3	3	3	3
Protect systems	Protect from water damage (corrosion or expansion)	3	3	3	3	3	3	3
	Protect from wind damage (corrosion or expansion)	3	3	3	3	3	3	3
	Protect from fire damage (corrosion or expansion)	3	3	3	3	3	3	3
Transportation aid	Support ease of transportation		3	3	3	3	3	3
		7260	225	378	378	378	378	378

Figure 6.17. Module frame QFD 2

Interface systems QFD 1

			Ensure structural integrity		Support geometric flexibility		Interface	Protect systems			Assembly (on-site)			
			Module structural integrity	Support internal mounts	Support adjustability	Support add-ons	Align module	Protect from water damage	Protect from wind damage	Protect from fire damage	Accuracy of assembly	Strength of connection	Ease of installation, alignment and integration	Module system stacking ability
Design	Cost	£	3	3	3	3	3	3	3	3	1	1	1	1
	Low number of finishing flaws		9	9	1	3	9				9	9	9	9
	Strength and rigidity	N or Nm	9	9	1	9	9				9	9	9	9
	Light weight	Kg	9	9	1	1	1							1
	Dimensions restrictions	h 3.4m (+-0.25), w3.4m, L12m, Hight internal: 2.5 - 2.6m	9	9							9	9	9	9
Safety	Low number of safety hazards		9	9	3	9	9							
Quality / Assurance	Corrosion protection						9	9	9	9				
	Reduce acoustic leakage		9				9							
	Reduce thermal leakage		9				9							
	Protect from rain & wind forces		9				9							
	Performance retention		9	9	9	9	9				9	9	9	9
Sustainability	Long lasting components	60 Years	9	9	9	3	9	9	9	9				
Manufacturing (off-site)	Ease & accuracy of manufacturing		9	9	9	9	9							
	Ease & accuracy of assembly		9	9	9	9	9							
	High standardisation level		9	9	9	9	9							
	Ease of quality control		9	9	9	9	9							
	Low cost and predictable supply chain		9	9	9	9	9							
Transportability	Transportable size		9	9									1	
	Reduce transportation damage		9	9	1	9								
			156	129	73	91	130	21	21	21	37	37	38	38

Figure 6.18. Interface systems QFD 1

Interface systems QFD 2		Interface mounts	Interface rack
Ensure structural integrity	Module structural integrity (internal and external loads)	9	9
	Support internal mounts	9	9
Support connections and flexibility	Support adjustability	3	3
	Support add-ons	9	9
Interface	Align module	9	
Protect systems	Protect from water damage (corrosion or expansion)	3	3
	Protect from wind damage (corrosion or expansion)	3	3
	Protect from fire damage (corrosion or expansion)	3	3
Assembly (on-site)	Accuracy of module assembly	9	9
	Strength of module connection	9	9
	Ease of installation, alignment and integration	9	9
	Module system stacking ability	9	
		6312	4800

Figure 6.19. Interfaces systems QFD 2

Interface rack QFD 1

			Connect with floor and frame	Connect with celling and frame	Connect with walls and frame	Support module alignment	Support ease of module assembly	Support bolting options	Strength of connection Mechanism	Waterproofing and vapour resistance	Reduce Acoustic Leakage	Protect from rain & wind forces	Protect fire damage
Design	Cost		3	3	3	3	3	3	3	3	3	3	3
	Low number of finishing flaws		3	3	3	3	3	3	3	3	3	3	3
	Strength and rigidity		9	9	9	9	9	9	9				
	Light weight		3	3	3	3	3	3	3	3	3	3	3
	Material		3	3	3	9	9	9	9	9	9	9	9
	Dimensions restrictions	Area, Length, width, height, tolerance	9	9	9	3							
Safety	Low number of safety hazards		1	1	1	1	1	1		1	1	1	1
Quality / Assurance	Corrosion protection									9	3	9	9
	Performance retention	Stiffness	9	9	9	9	9	9		9	9	9	9
Sustainability	Long lasting component		9	9	9	9	9	9		9	9	9	9
Manufacturability	Quality finishing		3	3	3	9	9	9	9	9	9	9	9
	Ease & accuracy of manufacturing	Rolling & shaping	9	9	9	9	9	9	9				
Assembly (offsite)	Ease & accuracy of part assembly	Welding, screwing, and anchoring	9	9	9								
	Ease of quality control		3	3	3	3	3	3	3	3	3	3	3

Figure 6.20. Interfaces rack QFD 1

Bathroom pod QFD 1

		Ensure structural integrity					Deliver services and water				Support sanitary activities					Remove waste	Protect systems		Support				Transportation compliance
		Modular structural integrity	Loading integrity	Structural alignment	Enclose room	Utilities structural support	Control water pressure	Control water temperature	Run lighting	Deliver electricity	Support heavy washing	Support light washing	Provide toilet facilities	Support preparation	Support accessories	Remove dark water	Protect from water damage	Protect from electrical damage	Provide electricity	Provide ventilation	Provide moisture reduction	Heating	Support ease of transportation
Safety	Low number of safety hazards				3				1	1	3	3	3		1	3		9	3	3	3		1
Privacy	Provide seclusion and privacy				9																		
	Ease of access				9																		
Comfort	Satisfactory lighting								9	9													
	Comfortable room temperature																					9	
	Comfortable water						9	9															
	Good quality air																			9	9		
Design	Ease of utilisatiation						9	9	9	9	9	9	9	9	9	9				9	9	9	9
	Aesthetically pleasing				9		9	9	9		9	9	9	9	9					9	9	9	
	Provide utilisation options						9	9	9		9	9	9										
	Size				9																		
	Cost	3		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Low number of finishing flaws	3		3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	Large number of layout options										9	9	9	9	9								
Quality / Assurance	Corrosion protection				9												9			3	9		
	No/Low air leakage				9																		
	Reduce acoustic leakage				9																		
	Reduce thermal leakage				9																		
	Reduce internal water leakage										9	9	9	9									
	Reduce external water leakage				9																		

Figure 6.21. Bathroom pod QFD 1 (Part 1)

		Ensure structural integrity					Deliver services and water				Support sanitary activities					Remove waste	Protect systems		Support				Transportation compliance
Bathroom pod QFD 1		Modular structural integrity	Loading integrity	Structural alignment	Enclose room	Utilities structural support	Control water pressure	Control water temperature	Run lighting	Deliver electricity	Support heavy washing	Support light washing	Provide toilet facilities	Support preparation	Support accessories	Remove dark water	Protect from water damage	Protect from electrical damage	Provide electricity	Provide ventilation	Provide moisture reduction	Heating	Support ease of transportation
Sustainability	Long lasting components	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
	Energy consumption						9	9	9	9	9	9										9	
Maintainability	Fast cleaning and maintaining				9				9		9	9	9	9	9	9							
Design flexibility	Upgrade flexibility	9		9	9	9	9	9	9		9	9	9	9	9	9							
	Configurability	3		3	3	3	3	3	3		9	9	9	9	9	9							
	Adjustability			9			9	9	9	9	9	9	9	9	9	9						9	9
Manufacturing /Assembly (off-site)	Ease of manufacturing	9		9	9	9	1	1	1	1	1	1	1	1	1	1						1	3
	Ease of assembly	9		9	9	9	1	1	1	1	1	1	1	1	1	1						1	9
	High standardisation level	9		9	9	9	3	3	3	3	3	3	3	3	3	3						3	9
	Ease of quality control	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Assembly (on-site)	Ease and accuracy of installation			9																			9
	Strength of connection			9																			
Transportability	Transportable size				9																		
	Reduce transportation damage	9	9																				9
	Lifting ability	3	1																				9
		63	22	78	69	51	47	47	56	35	62	62	53	53	53	53	12	12	12	12	12	35	69

Figure 6.22. Bathroom pod QFD 1 (Part 2)

Bathroom pods QFD 2		Structure															Facilities												
		Frame	Base					Walls				Access panels	Ceiling	Support			Bath			Wash/hand basin			WC/bidet			Shower			
		Frame	Concrete	Glass fibre sheet	Resin	Box section	Wisa/marine ply	Wall 1	Wall 2	Wall 3	Smart wall	Door	Ceiling	Services manifold	Access panel	Extraction vent	Tub	Taps	Waste outlet	Tap	Hot and cold incoming	Waste outlet	Cistern	Waste	WC sub frame	Brassware/controls	Shower head	Pre-formed shower tray	Divider
Ensure structural integrity	Modular structural integrity	9	9	9	3	9	9	9	9	9	9		9	9															
	Loading integrity	9	9	9		9	9	9	9	9	9		9	9															
	Structural alignment and integration	9																											
	Enclose room	9	9	9	3	9	9	9	9	9	9	9	9																9
	Provide accessibility											9			9														
	Utilities structural support													9	9										9				
Deliver services and water	Control water pressure																	9		9	9					9	9		
	Control water temperature																	9		9	9					9	9		
	Run lighting																												
	Deliver electricity																												
Support sanitary activities	Support heavy washing																9	9	9							9	9	9	
	Support light washing																			9	9	9							
	Provide toilet facilities																						9	9	9				
	Support preparation																												1
	Provide a comfortable environment																												9
Remove waste	Remove dark water																		9			9		9					
Protect systems	Protect from water damage/spillage				9	9	9	9	9	9	9	9	9				9	9											9
	Protect from electrical damage																												
Support	Provide ventilation															9													
	Reduce moisture															9													
	Provide heating																												
Transportation	Support ease of transportation																												
		3006	2250	2250	927	2493	2493	2493	2493	2493	2493	2187	2493	1620	1314	972	1287	2979	1287	2655	2655	1206	855	1098	1656	2736	2736	1044	2400

Figure 6.23. Bathroom pod QFD 2 (Part 1)

Bathroom pods QFD 2

		Fit out																				
		Finishes			Electrical				Furniture								Plumbing		Heating	Interface systems		Transportatio
		Tile	Paint	Vinyl	Lighting ring	Electrical outlet and wiring	Heated towel rail	Shaver socket circuit	Vanity unit	Shower screen	Mirrors	Cupboards	Grab rails	Hoists	Soap dish	Toilet roll holder	Waste outlets	Incoming hot and cold	Radiator	Metal stud and track	Interface systems	Lifting aids
Ensure structural integrity	Modular structural integrity																			3	3	
	Loading integrity																				9	
	Structural alignment and integration																			9	9	
	Enclose room	9	3	9																		
	Provide accessibility																					
	Utilities structural support																					
Deliver services and water	Control water pressure																	9				
	Control water temperature																	1				
	Run lighting				9	3																
	Deliver electricity					9																
Support sanitary activities	Support heavy washing														1		9	9				
	Support light washing														1		9	9				
	Provide toilet facilities															9						
	Support preparation					1	9	9	9	1	9	9	9	9	9							
	Provide a comfortable environment	9	1	1	9	9	1	1	1	9	1	1	9						9			
Remove waste	Remove dark water																9					
Protect systems	Protect from water damage/spillage	9	9	9						9							3					
	Protect from electrical damage						9		9													
Support	Provide ventilation																					
	Reduce moisture																					
	Provide heating																		9			
Transportation	Support ease of transportation																					9
		2313	791	1745	1179	1950	1043	854	1043	969	854	854	1422	783	1006	855	2331	2907	1251	963	1161	765

Figure 6.24. Bathroom pod QFD 2 (Part 2)

6.3.2. HQFD for requirements traceability

The HQFD model also supports requirements traceability by capturing dependencies among requirements at different levels. These dependencies can be used to trace how various requirements are connected to one another.

By examining the dependencies between requirements in the HQFD model, traceability flow diagrams can be generated (see Figure 6.25). A traceability flow diagram can aid in the identification of interrelated product requirements across several product levels. It shows how one product requirement at a higher product level (e.g. level 3: apartment module) has relationship with requirements at lower product level. It also shows how requirements are tied to one product component (e.g. interface rack). Requirement traceability flow diagrams can be used to facilitate understanding of responsibilities and requirements fulfilment of a construction product. Through the traceability flow diagrams, the HQFD model provides a fast, easy and comprehensive visual understanding of requirements as illustrated in Figure 6.25.

The traceability flow diagram also presents how a tangible and traceable solution are related (i.e. understanding the interconnectivity of top-level requirements on a set of lower level requirements). The diagram illustrates interrelated functional requirements across a set of product levels (marked in orange). Functional requirements marked in white are mapped to other product segments (not highlighted in this example). Requirements marked in yellow are non-functional requirement, which are turned into functional requirements at lower product levels. This example emphasises the effectiveness of the HQFD model at capturing the interrelationship of complex requirements.

The relationship between requirements are not standardised and they often vary. Therefore, making traceability of interdependencies of requirements difficult. For instance, a top-level requirement might not be satisfied at one level of the HQFD structure. The information may trickle down to multiple levels, or even skip some levels and could have multilevel requirements solutions. The HQFD model helps to overcome this challenge by being able to capture the dependencies of requirements even if they are not standardised. In using the HQFD model, engineering solution can be managed for the fulfilment of complex systems through hierarchical QFDs.

The traceability flow diagram in this research was developed by mapping corresponding functional requirements associated with one higher level functional requirement (i.e. modular structural integrity). The higher level functional requirement is associated with the product segment “apartment module” (level 3). Subsequently all related lower level functional requirements were mapped to the higher level functional requirement (i.e. modular structural integrity). The lower level functional requirements were extracted from across 4 QFDs of the HQFD model, which represent 4 product levels of the overall apartment building.

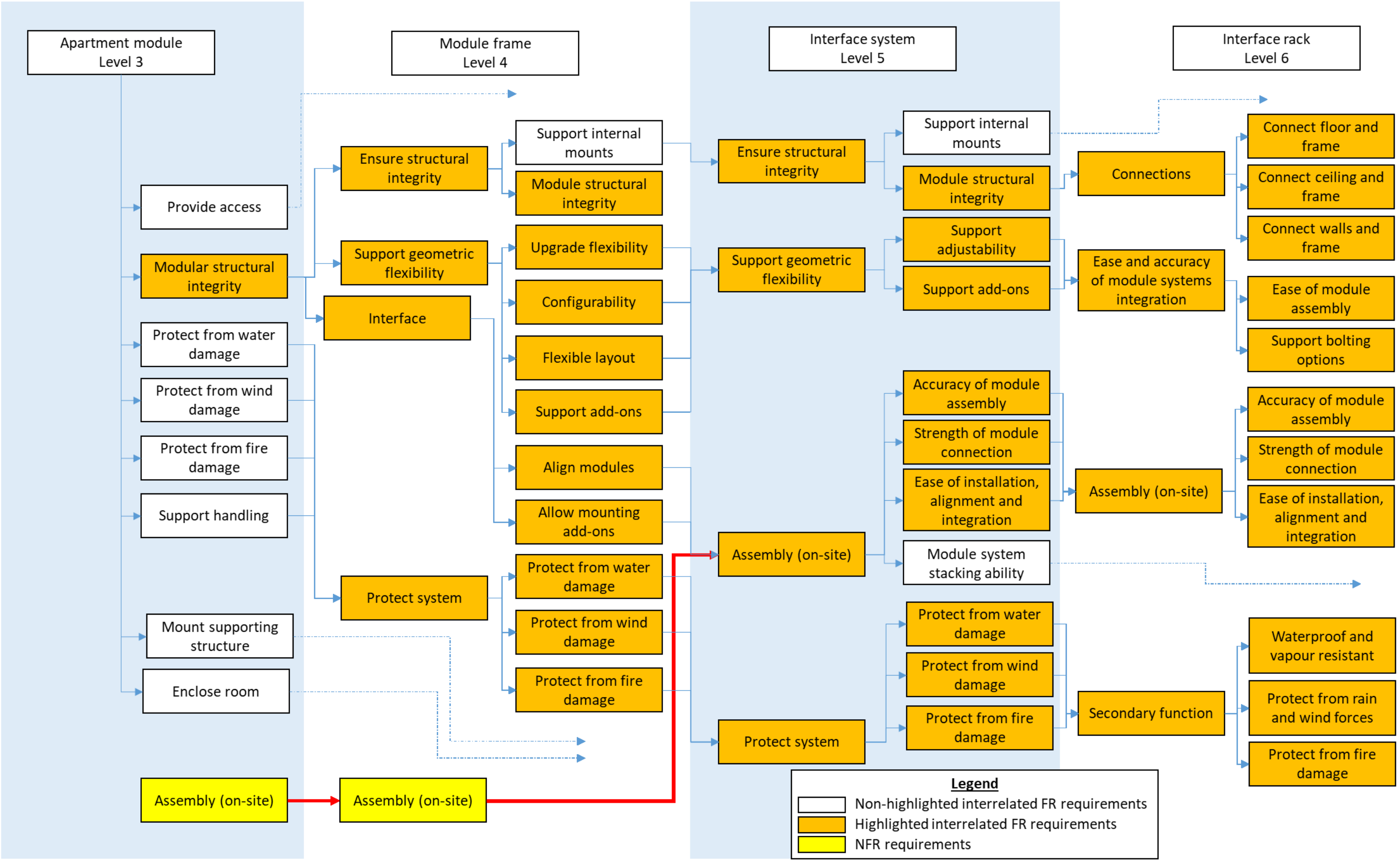


Figure 6.25. Traceability flow diagram

6.3.3. HQFD data analytics: the impact of advanced manufacturing and modular design on requirements

This research has applied data analytics through examining requirements weightings to evaluate the potential impact on requirements that “advance manufacturing and modular design” (AM&MD) has on construction products. The result (illustrated by Figures 6.26 to 6.37) suggests that a sizable redesign of the apartment building needs to occur in order to facilitate effective utilisation of manufactured construction products. According to the HQFD model, there are components (e.g. module frame) that need to be carefully designed to ensure the ease of manufacturing of the apartment module (see Figure 6.31). The data from the HQFD also shows that added complexity of manufacturing operation in construction substantially increase demands on the design of an apartment building. This was determined by comparing the difference in requirements weightings (i.e. design importance) of an AM&MD environment. The difference in weightings is approximately half the final AM&MD weighting value of product requirements of an apartment module, which suggest a significant amount of redesign is needed for the apartment building.

Figure 6.26 to Figure 6.37 present the results of the data analytics, which highlight the impact on the weight of the shift towards manufacturing-oriented requirements (indicated in orange). The remaining requirements weights that can be transferred from bespoke construction are represented in blue. The segmentation of the two types of requirements weightings (manufacturing-oriented and bespoke) provides an insight into the potential impact that a construction shift to manufacturing might have on requirements. For example, the “module structure integrity” of the bathroom pod has a AM&MD weighting difference of approximately 5 times that of bespoke, which suggests high importance for manufacturing-oriented construction (AM&MD).

Figures of various product segment weightings were developed to determine the potential impact that AM&MD has on requirements and product segments (non-functional requirements, functional requirements, and product systems). The product levels included in these data analyses cover apartment building, apartment module, modules frame, and bathroom pods. Table 6.2 provides a list of figures developed from the weightings data generated through the HQFD model in terms of product requirements and product systems importance**.**

Table 6.2. Requirements and product system weightings

Product level	Non-functional requirements graph	Functional requirements graph	Product systems graph
Apartment building (level 2)	Figure 6.26	Figure 6.27	Figure 6.28
Apartment module (level 3)	Figure 6.29	Figure 6.30	Figure 6.31
Module frame (level 4)	Figure 6.32	Figure 6.33	Figure 6.34
Bathroom pods (level 4)	Figure 6.35	Figure 6.36	Figure 6.37

The weights represent “non-functional requirements”, “functional requirements”, and “products systems” calculated through the QFDs of i) apartment building, ii) apartment module, iii) frame, and iv) bathroom pod. The data analytics provide additional insight into design consideration, areas of risk and resource allocation. The data analytic results for each of the four segments of an apartment building is presented below.

Apartment building: At the apartment building level, a large set of non-functional requirements (NFR) where added. These NFRs display potentially large portions of the NFR impact index value. The HQFD model suggests that the significance of the new NFR is large compared to bespoke NFRs. The impact of AM&MD on “apartment building” functionality is not wide spread but limited to half of the functional requirements – focussing mainly on functions associated with habitable living and structural integrity. There is also an indication for high potential impact on “running services” (e.g. water, heating and electricity). According to the HQFD model, there is a wide spread impact on product systems. However, there were less effects on certain product systems such as foundation and fire systems. This implies that a large portion of the building may have to be redesigned in order to attain the full benefit of AM&MD.

Apartment module: This product segment is unique as compared with other examples covered in this chapter. Non-functional requirements for the “apartment module” are categorised into three different groups instead of two (i.e. bespoke, AM&MD1, and AM&MD2) (see Section 6.2.2). According to the HQFD model, the “apartment module” relationship with AM&MD is more complex than at other levels and many components may need to be redesigned.

Module frame: The frame is an AM&MD imposed component and is specific to AM&MD. The graph for frame product system highlights the significance of the "interfacing systems". According to the HQFD model, the "interfacing systems" hold significant importance for the fulfilment of frame requirements. It is recommended that high amount of design attention be allocated to these component systems.

Bathroom pods: For the bathroom pods, 4 new NFR categories were added. They include design flexibility, manufacturing, on-site assembly and transportability. They in turn resulted in wide spread and sizeable impact on functional and product systems domain across the HQFD. This implies that most of the bathroom pod may need to be modified for maximum potential of AM&MD.

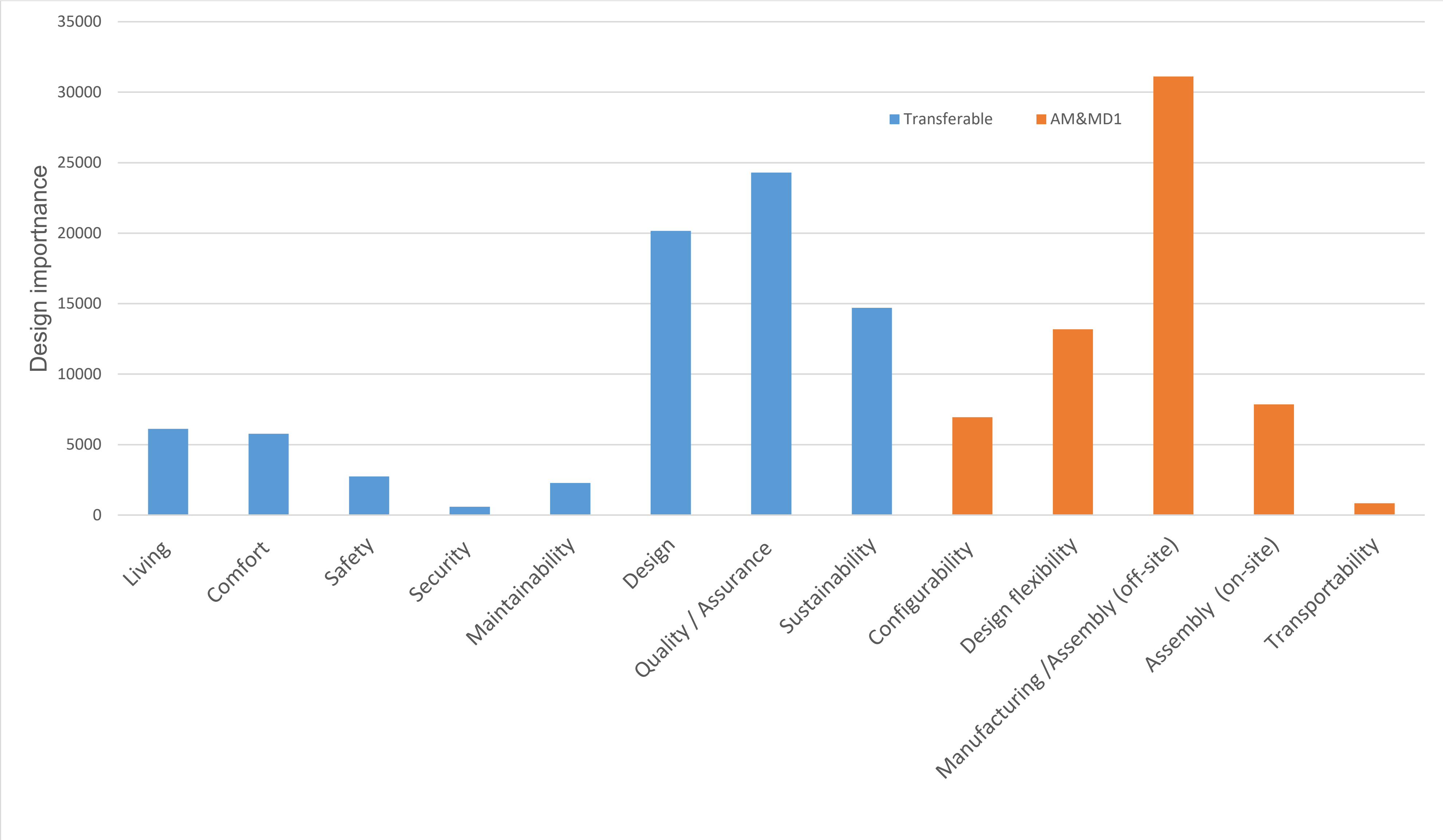


Figure 6.26. Apartment building design importance of non-functional requirements

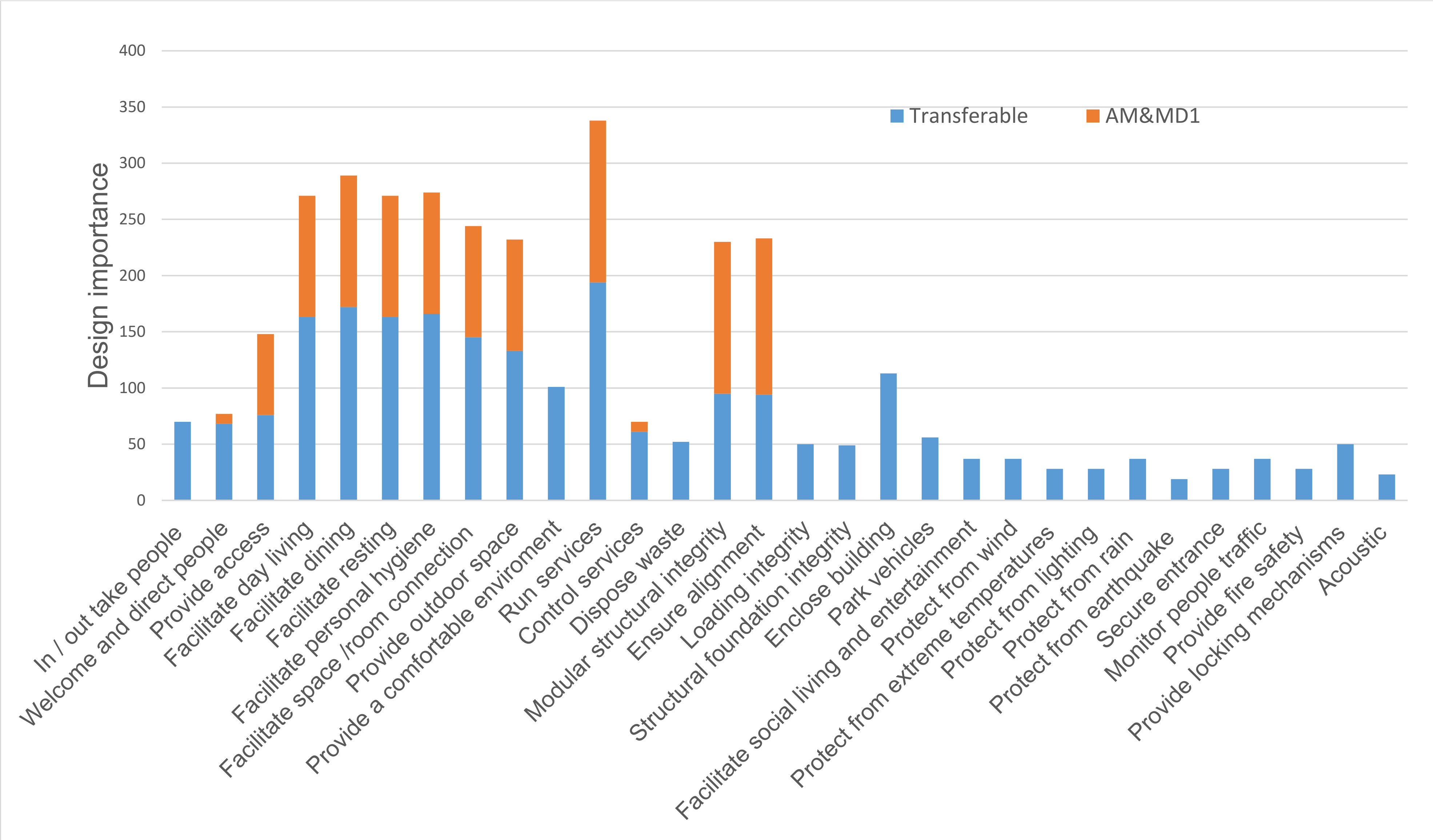


Figure 6.27. Apartment building design importance of functional requirements

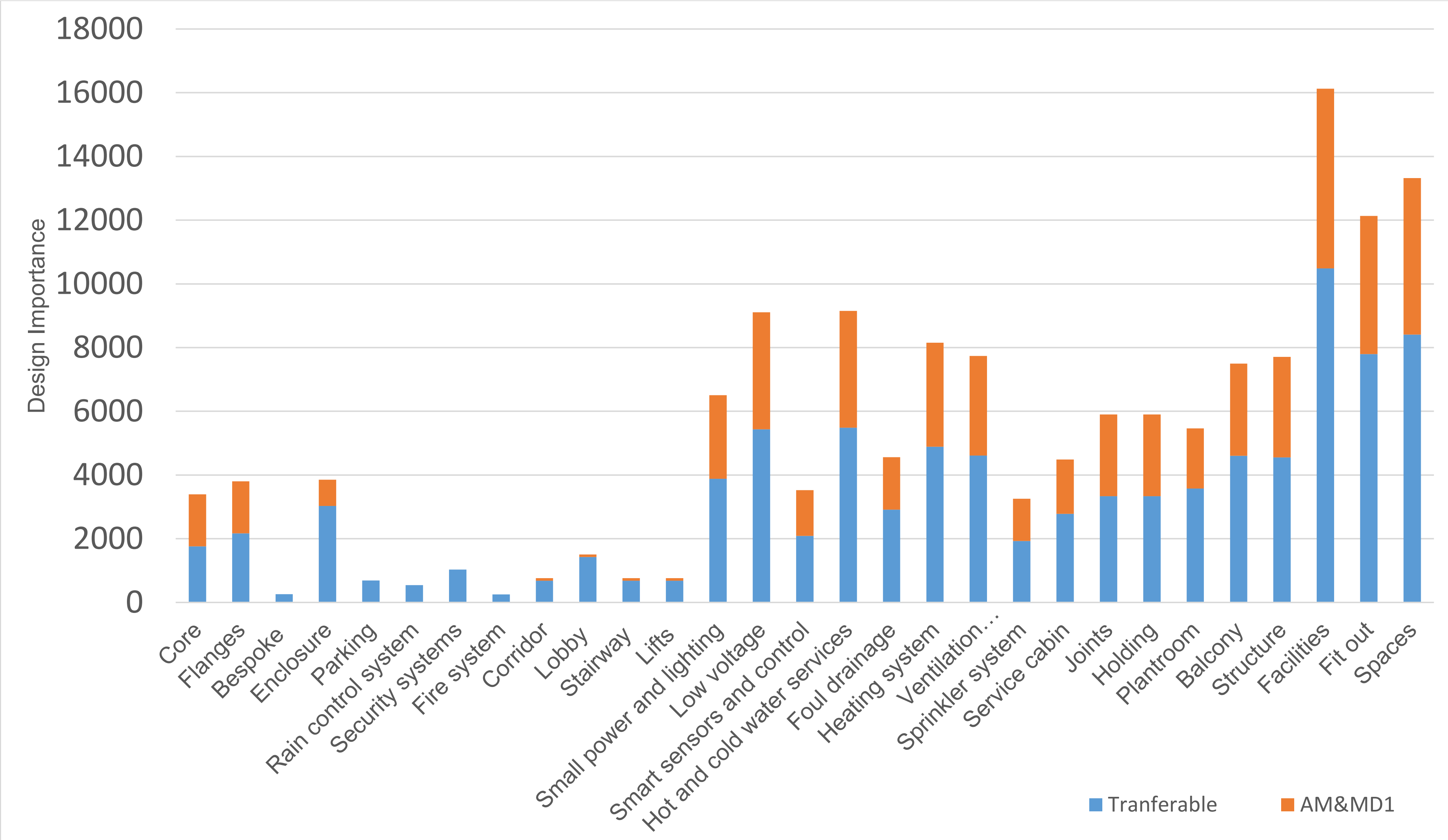


Figure 6.28. Apartment building design importance of product systems

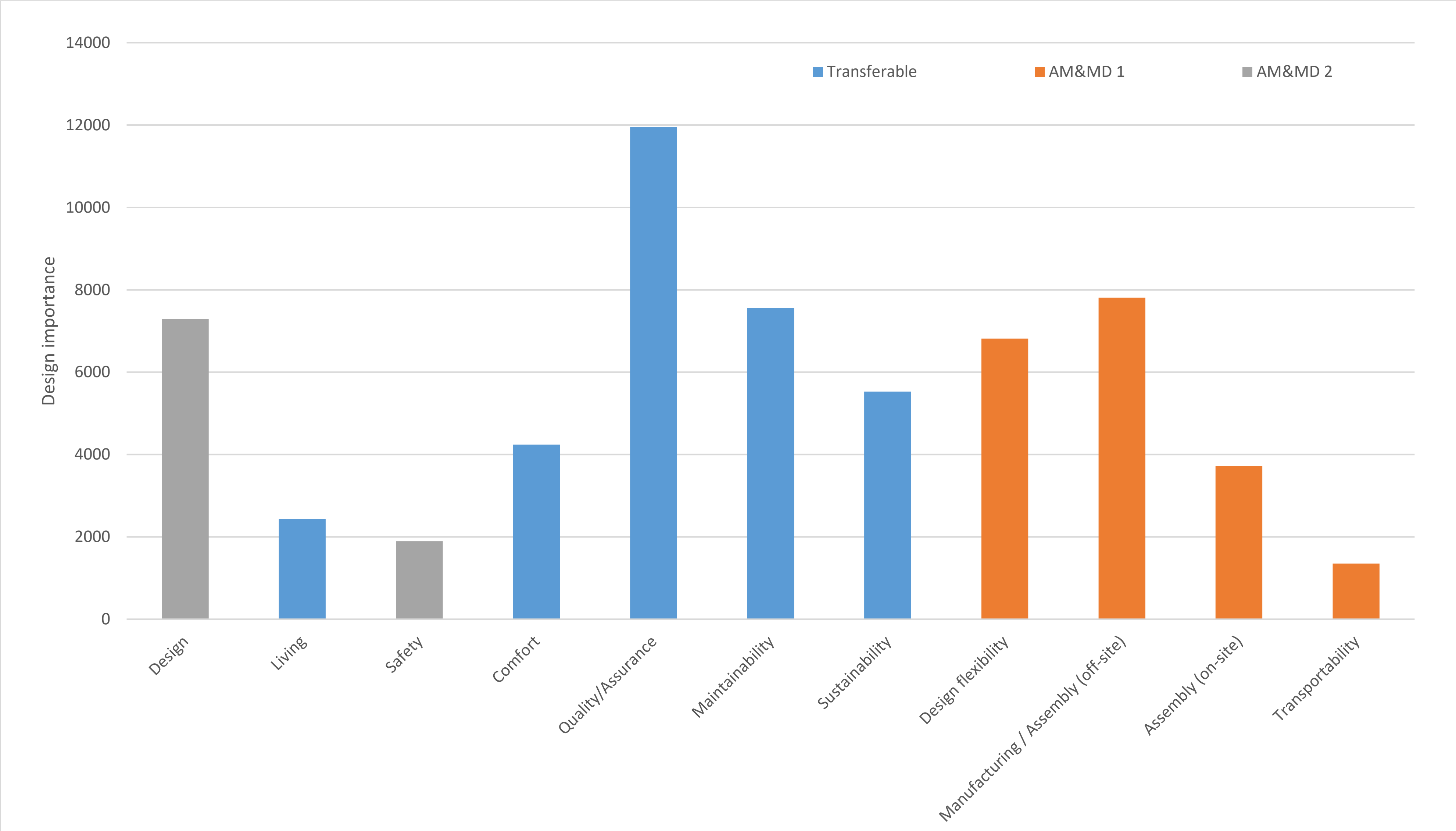


Figure 6.29. Apartment module design importance of non-functional requirements

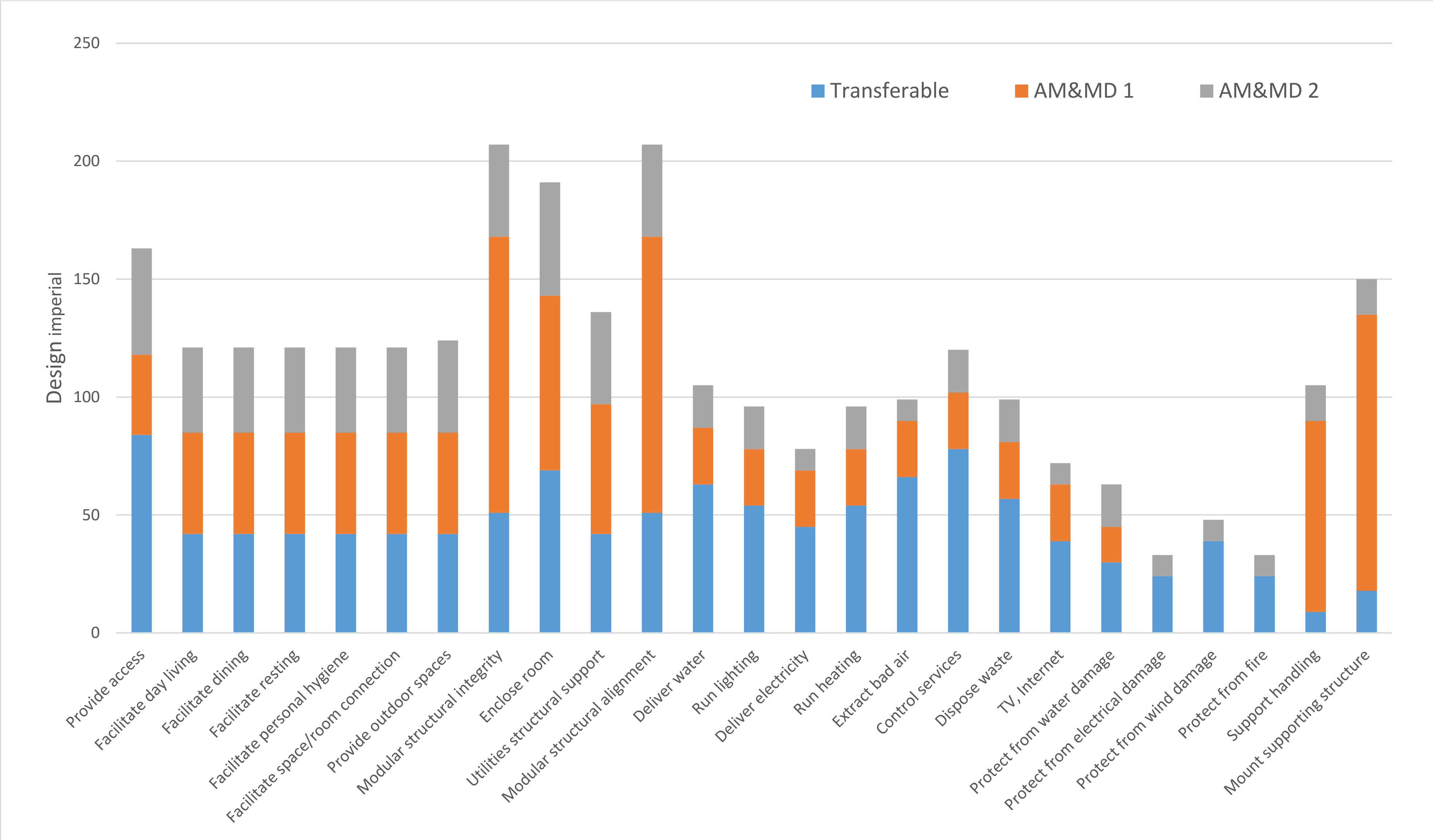


Figure 6.30. Apartment module design importance of functional requirements

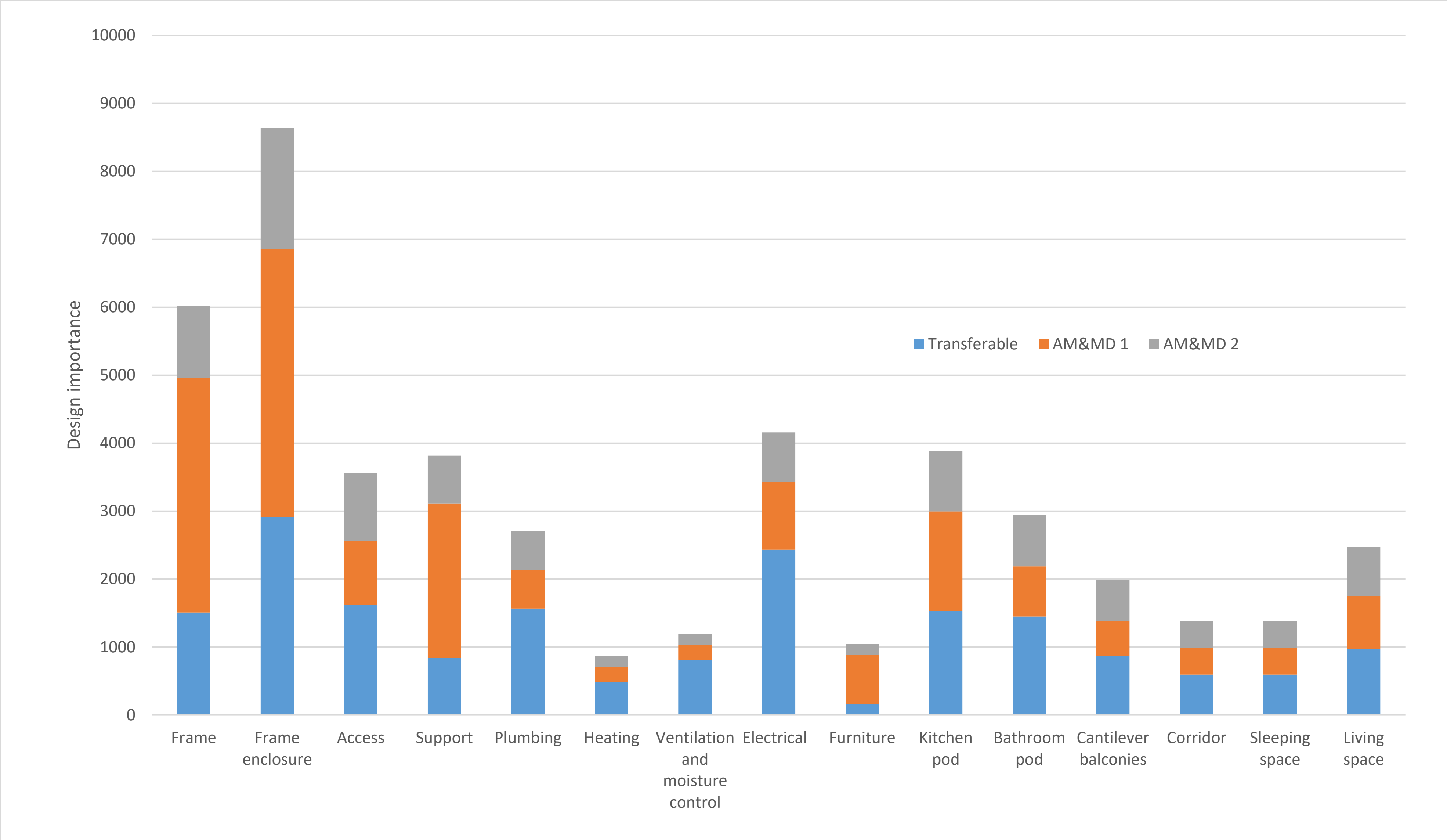


Figure 6.31. Apartment module design importance of product systems

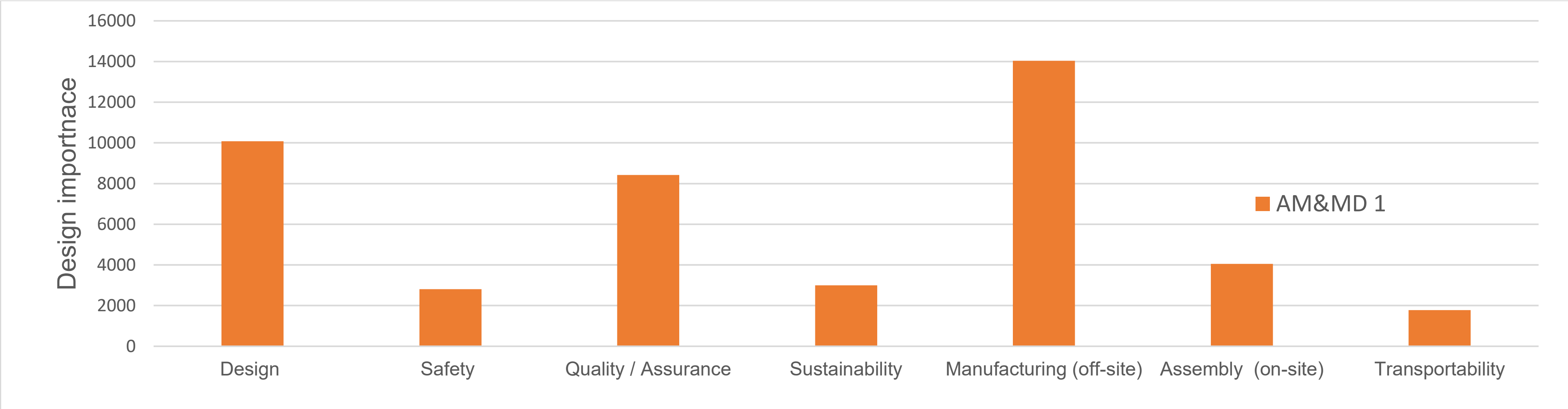


Figure 6.32. Module frame design importance of non-functional requirements

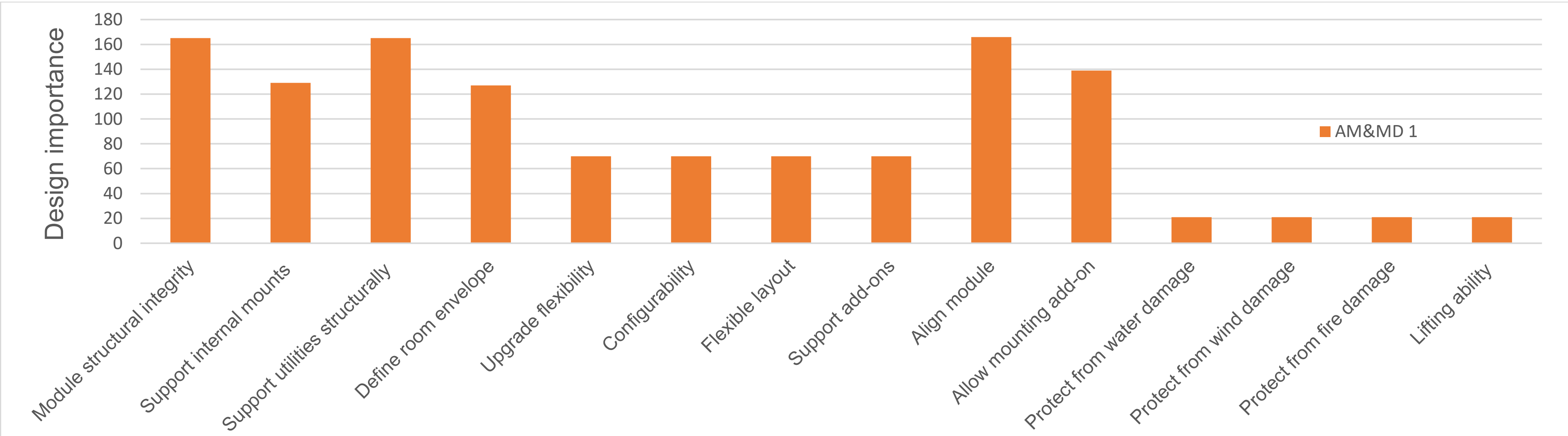


Figure 6.33. Module frame design importance of functional requirements

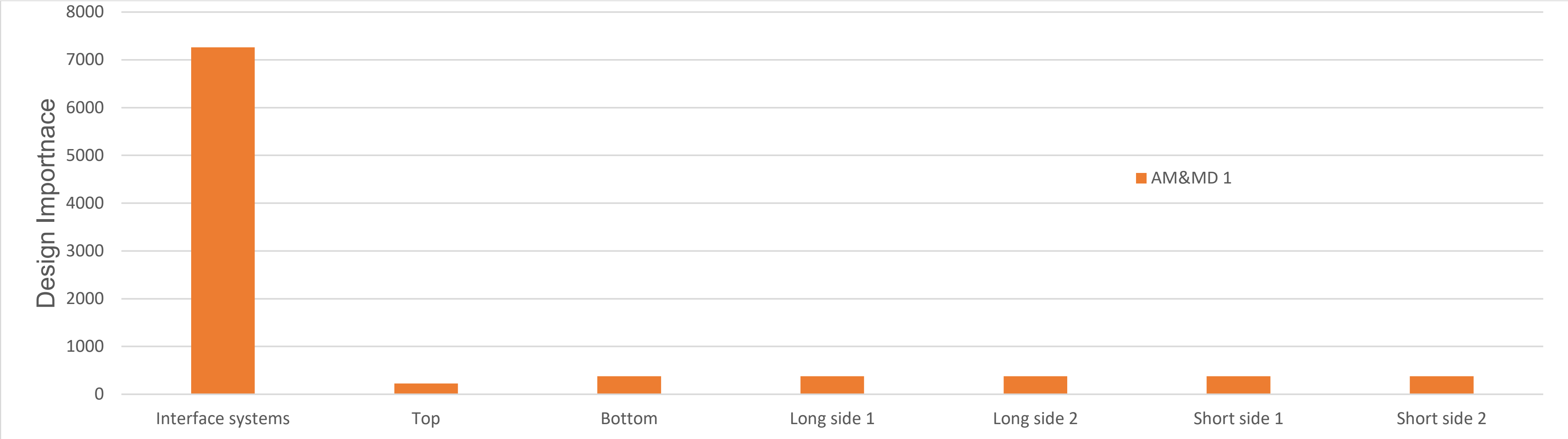


Figure 6.34. Module frame design importance of product systems

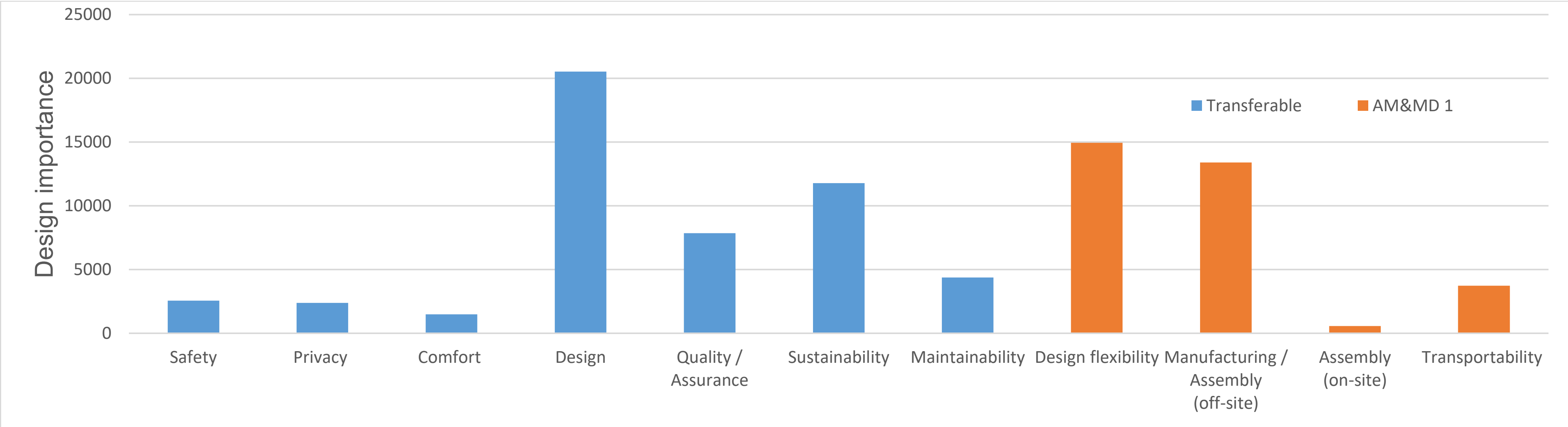


Figure 6.35. Bathroom pod design importance of non-functional requirements

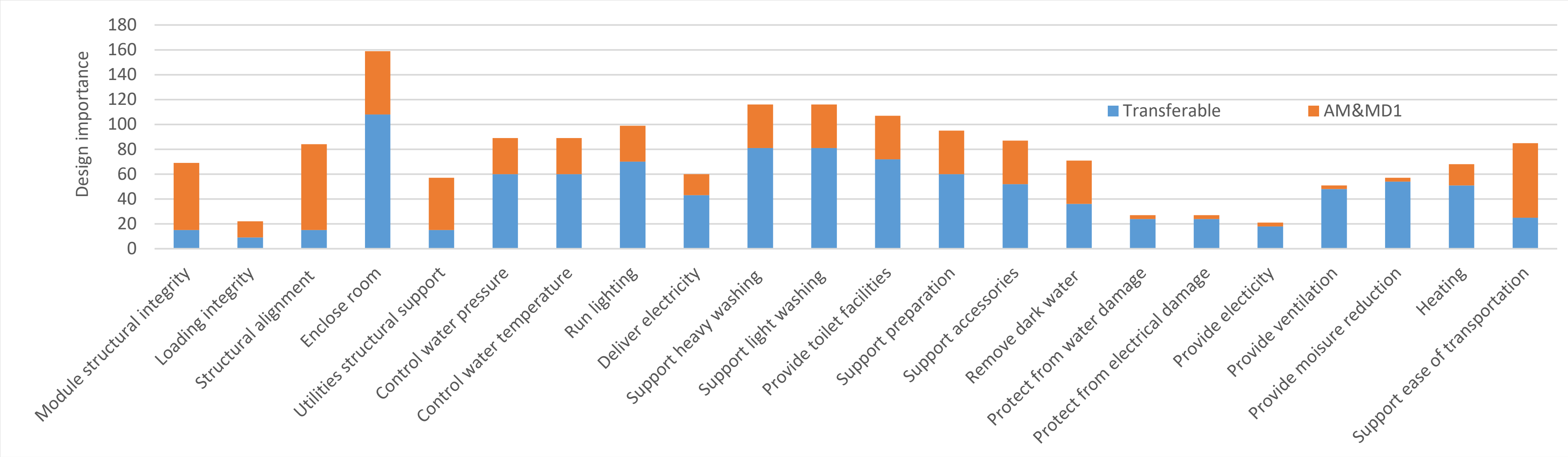


Figure 6.36. Bathroom pod design importance of functional requirements

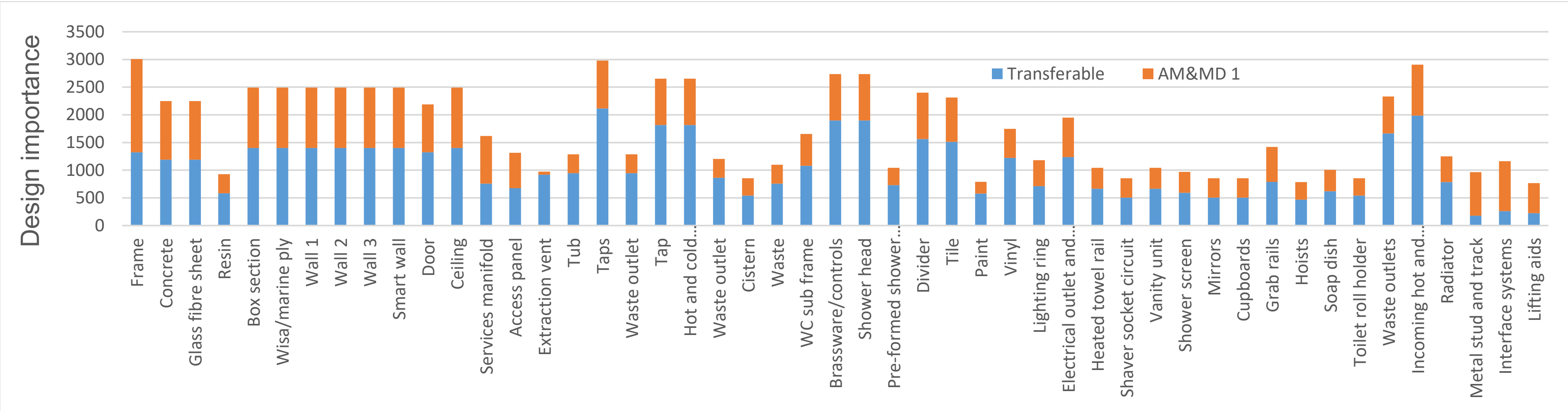


Figure 6.37. Bathroom pod design importance of product system

6.4. Discussion

A HQFD model was applied to address systematic requirements analysis of manufactured building systems. The model treats building systems as a complex system consisting of many different segments and dimensions. The HQFD model provides an option in assisting requirements analysis for manufacturing of complex construction products. It provides an alternative or addition to systematic tools for construction.

The model was able to handle all modular apartment building requirements as shown by the QFD models. The systematic nature of HQFD model helps addressed complexity management for requirements fulfilment and data analytics. It breaks complex problem down systematically into manageable parts and shows that it is possible to map requirements from top level to detailed level.

The HQFD model should be used to support product planning and requirements analysis, which should occur before the start of heavy project work. This will help determine the level of difficulties, complexity and potential pitfalls within product planning. It is to be used as a framework model and is recommended for short intensive sessions during the planning phase of a project. Specialist teams working on specific section of the building should develop their own QFD models, which can be quickly compiled or integrated to form the overall HQFD model for the apartment building.

The research work on the development of the HQFD model has also highlighted some key lessons and areas for future development.

6.4.1. Lessons learnt

The HQFD model was able to organise and connect 415 product requirements and product systems in a network of QFD matrixes across 5 product levels (discussed in Section 6.3.1). However, some lessons can be discerned from the application of the HQFD model. They include the following:

i) **More advanced structure and information management suited for complex systems.** The HQFD model facilitates the handling of complex systems than a simple QFD described in Chapter 5. It does this by providing a more advanced organisational and systematic information structure (including dimensions of domain, segments and levels). By examining the dimensions, the model supports the complex system to be analysed more comprehensively and in manageable parts. It also facilitates a more comprehensive understanding of requirements definition and their interconnectivity. In addition, the HQFD organisation structure provides a deeper understanding of requirements analysis information. The HQFD structure aides in closing logic holes that occur not just across QFD domains but also across HQFD segments and levels.

ii) **Synergistic advantages.** The HQFD model carries all benefits present in QFD with additional synergistic advantages. Some of these advantages include HQFD levels of interconnectivity, which support requirements traceability. The requirements traceability in turn supports requirements fulfilment needed for a manufactured construction product. This provides a quick and comprehensive way for requirements checking.

Two advances of requirements traceability as compared to QFD include i) the systematic breakdown of the complex systems from top to detailed level, which allows more manageable and insightful segmentation, and ii) traceability that supports the understanding of how top-level requirements can affect detailed level requirements. It is important to understand the interconnectivity aspect of the HQFD model and on the interconnection of information flows across the HQFD structure. Such understanding can help analyse product requirements, engineering systems and solutions.

iii) **HQFD data analytics application.** The high level of requirements dependencies in the HQFD model presents a network of interconnected elements (e.g. product requirements and product systems), which provides an environment for data analytics application. An example of data analytics was made in this chapter, which indicates building construction requirements most likely to be affected by a shift towards manufacturing production systems (see Section 6.3.3). The HQFD model contains a significant amount of valuable requirements data of a manufactured apartment building. This data source was used to identify potential areas for future development of modular building products.

The HQFD data analytics can help further understand phenomenon in construction. For instance, HQFD data analytics can be used to identify areas for prioritisation of business activities and product features to facilitate better resource allocation (see Chapter 5). Other applications of HQFD data analytics could involve identification of product features that could be more easily manufactured, support better risk management and organisation of an efficient business organisation.

iv) **A framework for future development of building systems.** The abundance of information available to an engineer can turn HQFD model into a potential platform to launch innovation for development of future products.

6.4.2. Consideration for future development

Although there are strong arguments for the HQFD model, there are also several issues that need to be addressed regarding utilisation of it. These issues include the following:

i) **Experts dependent**: Although the HQFD model has the benefit of reducing dependences on product developments and design expertise, it itself is heavily reliant on experts' inputs for the initial development of the model. It is recommended that future HQFD model development should be more data driven and automated.

ii) **It has difficulty in administration**: HQFD model is not a simple tool and utilisation of it requires training. One down side of the model is that it is resources heavy and requires a considerable amount of time and diligence to develop. The upside is that the technical work of the model only needs to be developed once.

iii) **Protocols development and digital support:** In order to facilitate the development of future HQFD model, it is recommended that protocols be developed so that corporate culture embraces the data recording practices needed for HQFD model development. Future development of HQFD model could address the difficulty and complexity in the implementation of the model.

iv) **Additional analytics:** Other forms of analysis need to be considered to increase the level of analytical support that the HQFD model can provide. Further advancements of the HQFD model could include data analytics by targeting on more specialised analyses such as risk management, resource allocation, business organisation and efficiency.

6.5. Conclusion

This chapter presents an application of a HQFD model in requirements management and product planning in a modular construction environment. Past applications of this approach to requirements analysis were limited to QFD models of mainly buildings or construction operations. The model maps requirements not just at a singular product level (e.g. bathroom pod) but on a set of related products that make up an entire building, which resembles a complex system.

The HQFD model breaks a complex problem down systematically into manageable parts. It further shows that it is possible to map requirements from top level to detailed level. It was able to organise requirements of a modular apartment building across a set of domains, levels and segments. The model also provided a platform for traceability and generated further information for data analytics application. The HQFD model can help to assess the level of difficulties, complexity and potential pitfalls within product planning in construction.

This research has provided a step forward in the development of systematic tools for management of complex construction products, which involve multi-dimensional and interconnection of multilevel consideration. Future work in product planning for manufactured building systems should utilise more systematic tools such as HQFD for planning and information modelling.

Chapter 7

Modularisation in Construction

7.1. Introduction

To enable further industrialisation of the sector through off-site construction there is a need to acquire more capabilities in advanced manufacturing (Höök 2006; and Marchesi et al. 2013) and product planning. Specifically, the industry needs to define flexible and efficient product and production systems that are adaptable to rapidly changing requirement conditions imposed by clients, technological development, business considerations and other corporate reasons. It also needs to undertake more rigorous product planning as this is key to prevent logic holes and lost resources, and allow the management of product variations and the identification of pathways to achieve engineering targets (Wee et al. 2017a).

Modularisation is increasingly applied in the construction sector to handle product variations and manage product complexity issues (KPMG 2016; and Wee et al. 2017b). Modularisation supports the clustering of different product sub-systems or components into modules to increase the flexibility of the overall product system and manage complexity (Borjesson and Hölttä-Otto 2014). It is useful for handling product variations and reducing redesign work (Simpson et al. 2012). Modularisation enables quicker and easier reconfiguration of products to meet customised demands without massive alterations of the product or production operation. Modularisation is typically supported by the use of product configurators, (i.e. software tools), which help select and configure existing components to develop new products.

Despite the expected value of modularisation tools, research on their application to achieve further efficiency in construction has been limited (Gilbert et al. 2013). This is mainly due to the challenge of determining effective tools for supporting efficient developments of building modular products. There is therefore a need to undertake further research in construction to understand which modularisation tools can help manage product variations and achieve cost efficiency.

This chapter presents a multi-driver modularisation approach to support the design and off-site construction of construction product. The research is based on a case study applied on a plantroom product, which involved two research stages (see Studies 4 and 5, and Chapter 3) and was conducted in collaboration with engineers at Laing O'Rourke. The approach is intended for construction products that are well-defined segments of a building and can be independently developed along the building supply chain (e.g. bathroom pods, kitchen pods, plantrooms, MEP systems, and balconies). This work does not address volumetric builds or an entire building's architecture. The *first research stage* examines the application of three modularisation tools, namely the dependency structure matrix (DSM), the modular identification matrix (MIM), and the generational variance index (GVI). The *second research stage* proposes the aforementioned multi-driver approach to modularisation. Three modularisation drivers were prioritised and used (i.e. technical specification, manufacturing and common unit) to inform the development of the final design. These drivers were addressed through specific modularisation tools (i.e. DSM, GVI, Cost Weightings (CW) and the coupling indexes (CI)).

The approach proposed in this research has been formulated by drawing upon modularisation techniques developed outside of construction sector and tailoring them to construction operation and conditions. This work aims to support companies intending to shift their operation towards manufacturing of construction products by improving and facilitating the manufacturing process through effective modularisation. The research focuses on the construction condition that influences modularisation and how modularisation is to be conducted. This work specifically considers systematic and algorithmic modularisation tools as they allow for more detail analytics.

The remainder of this chapter is organised as follows: Section 7.2 describes the methodology utilised for the evaluation of DSM, MIM and GVI. This section also describes the methodology used for formulating a multi-driver data driven approach for modularisation. Section 7.3 looks at the first research stage that is the evaluation of three existing modularisation tools (i.e. DSM, MIM, and GVI). Section 7.4 explores the second research stage, which proposes the multi-driver approach to modularisation. Section 7.5 discusses the key findings of the research, while section 7.6 concludes.

Despite the existence of multiple modularisation tools, determining which tools are effective at supporting the development of modular products in construction is challenging. Both Gilbert (2013) and Veenstra (2006) highlight the value of modularisation tools and their applicability in construction. However, they did not address the nature of the modularisation problem in construction and did not consider the issue of modularisation drivers. Gilbert focusses on module functionality (i.e. technical specification), and Veenstra focuses on product platforms (i.e. common unit or standardisation). There is a need to consider multiple modularisation drivers in the definition of modules. Although both Gilbert and Veenstra have worked on modular construction, there is a need to undertake research on up market modular products specific to advanced off-site construction and understand how to manage modularisation issues.

This research focuses on DSM, MIM, and GVI, which are commonly used in other engineering disciplines (e.g. mechanical engineering, robotics, automotive, and consumer electronics) (Borjesson 2010). These three tools are systematic and analytical in nature. They provide desired benefits in terms of data analytics, allowing for the identification of strategic advantages. DSM is the most effective for dealing with dependency issues in product. MIM is specifically designed to incorporate business strategy into product development. GVI combined with another index (e.g. CI) is one of the most effective ways of determining a product platform.

7.2. Methodology

This research is based on a modularisation case study consisting of two research stages (see Study 4 and 5 in Chapter 3). The first determines the suitability of different modularisation tools to support the building design process. The second addresses a multi-driver modularisation problem using a data driven approach. Both research stages focused on a plantroom product (see Figure 7.1 and Figure 7.2).

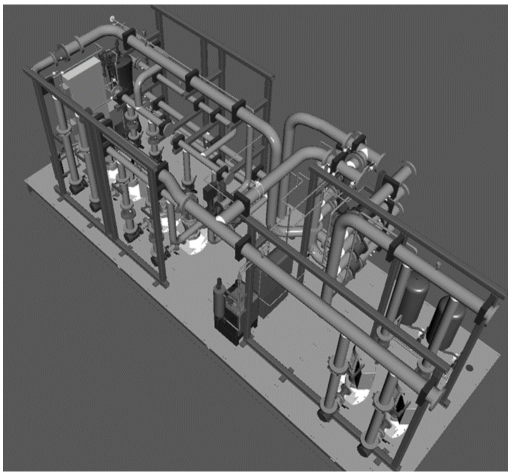


Figure 7.1. Integrated plantroom product
(Source: Laing O'Rourke)

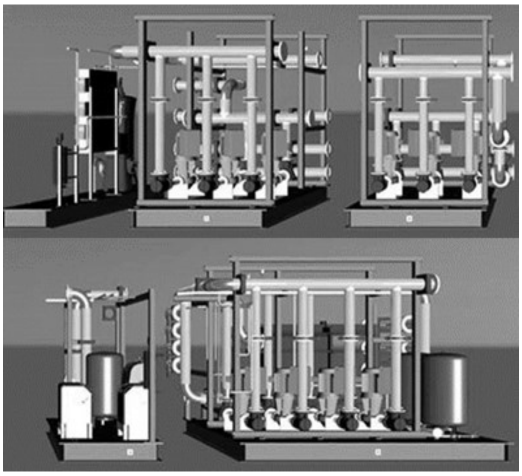


Figure 7.2. Modularised plantroom product (Source: Laing O'Rourke)

7.2.1. Research stage 1: Evaluation of modularisation tools

Three different tools, namely DSM, MIM and GVI were implemented to modularise a plantroom (see Figure 7.3). Each tool was evaluated to determine its effectiveness at tackling a single or multiple modularisation drivers. The methodology of the study involved: i) collection of information about the product case to be studied; ii) compilation of modularisation drivers; iii) implementation of the three modular tools to the plantroom design; and iv) evaluation of the three tools to establish which of them would best satisfy the modularisation drivers.

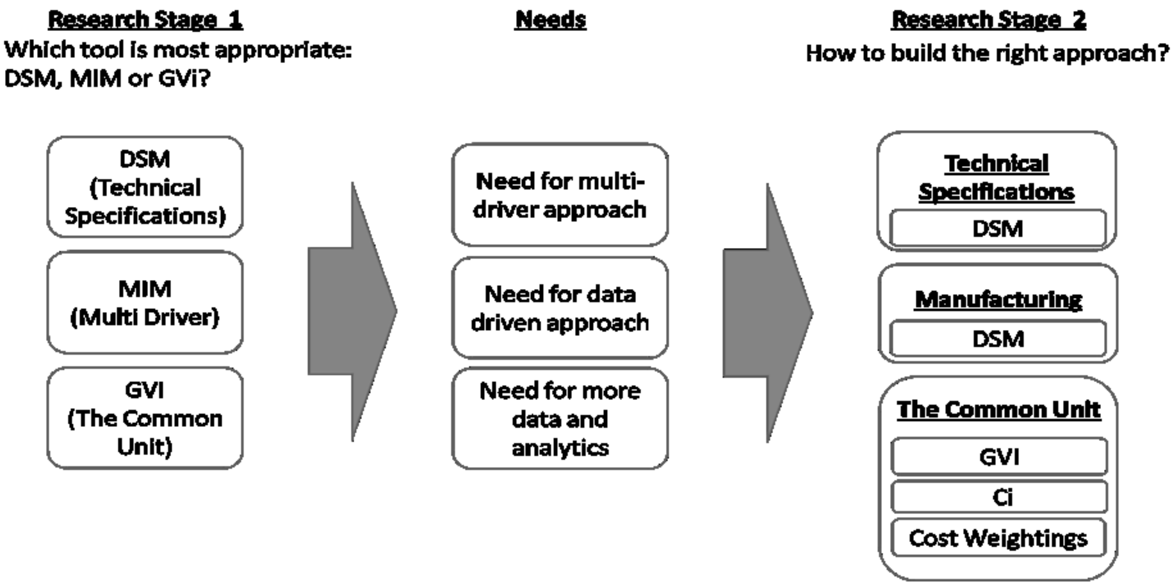


Figure 7.3. Research stage 1 and research stage 2

Collection of product information. Knowledge about the plantroom product is required to implement the modularisation tools. This was acquired through a reverse engineering process, which comprised examination of existing product documentation and discussions with engineers from the collaborating company. Various product documents were examined including product manuals, CAD files, schematics and bills of materials. A simplified version of the product schematic is illustrated in Figure 7.4. The product schematic illustrates the mechanical characteristics of the plantroom. A total of 14 product sub-systems are displayed including "building connection", "filtration", "dosing pot S1", "pump S1", "pump S2", "3 way valves", "pressure control S1", "degasser S1", "heat exchanger", "pressure control P1", "chiller connection", "degasser P1", "pump P1" and "dosing pot P1". It is noteworthy that the schematic includes mechanical sub-systems only, and therefore it excludes product sub-systems such as the "control panel" and the "structure".

Fifteen informal discussions were carried out with different groups of engineers from the collaborating company to investigate the plantroom design processes and to validate understanding of their engineering operations. Each of these discussions lasted between 15 and 120 minutes. The discussions took place at the collaborating company's main design offices and factories as part of periodic visits and during a one week secondment. The experts interviewed included mechanical engineers, design engineers and systems engineers who regularly work on plantroom products.

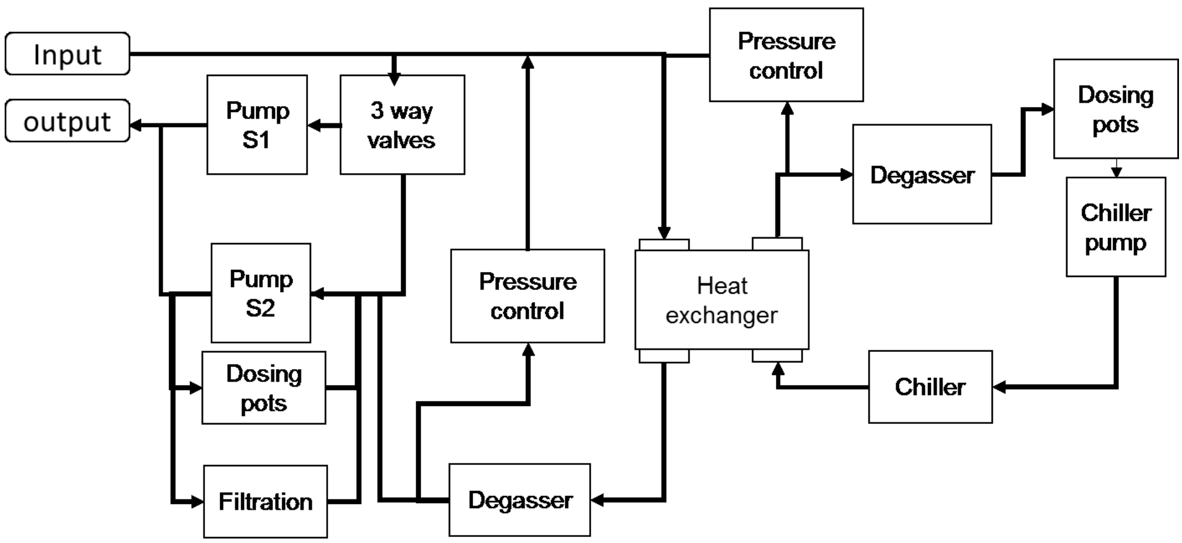


Figure 7.4. Simplified plantroom schematic

Compilation of the modularisation drivers. A list of fifteen modularisation drivers was produced based on a review of the academic literature (Erixon 1996; Hölttä-Otto 2005; and Borjesson 2010), and informal discussions with industry experts. Two types of modularisation drivers were identified (i.e. generic and construction specific). Generic modularisation drivers include *technical specification*, *styling*, *carry over*, *product planning*, *technology evolution*, *process specification*, *common unit*, *manufacturing*, *separate testability*, *purchasing*, *maintenance*, *product upgrading*, and *recycling*, while construction specific modular drivers comprise *transportation* and *architectural restrictions*.

Implementation of the tools. The three tools were then implemented.

- Design Structure Matrix (DSM): A component-based “function” DSM model was developed using the Cambridge Advanced Modeller software 2014. Two pieces of information were utilised to build the model: material flows (see Figure 7.3) and spatial preferences (e.g. accessibility). The former was collected directly from the product schematic (see Figure 7.3). The latter is based on safety and maintenance information as well as operational preferences and was elicited from engineers in the collaborating company.
- Modularisation Identification Matrix (MIM): The MIM model involves mapping the modularisation drivers against the product sub-systems extracted from the plantroom schematic. Information on the effect of modularisation drivers on product sub-systems was determined during the collection of product information (see Methodology section) and entered in the MIM model.
- Generational Variance Index (GVI): As part of work which is not reported in this research but is part of this project, a QFD model was developed for the plantroom (Wee et al. 2017a). The model maps non-functional requirements to functional requirements and then to product sub-systems using the QFD1 and QFD2 matrixes (Wee et al. 2017a). The QFD2 matrix which maps the functional requirements to the product sub-systems was used for the generation of the GVI. The information necessary to generate the matrix was collected from interviews with engineers at the collaborating company.

Preliminary evaluation. Two engineers in the plantroom design team of the collaborating company were interviewed in March 2017 to evaluate and rank the modular designs emerged from the application of the three tools. The engineers interviewed have 15 and 25 years of experience respectively. Both interviews took place at the collaborating company and lasted approximately 30 min and 60 min respectively. A questionnaire with open ended questions was prepared and used to guide the interviews. Some examples include determining the effectiveness of a modularisation outcome and ranking the priority of each modularisation driver. An example of this questionnaire can be seen in appendix 2.

The modular designs obtained through the three modularisation tools were also compared against a modularised reference model developed by the collaborating company. The variable used for comparison between the formers and the latter is the number of identical "sub-system to sub-system relationships" (SSR) within a distinct module.

7.2.2. Research stage 2: A multi-driver modularisation approach

From research stage 1 to research stage 2, there was a shift in focus from identifying the appropriate modularisation tool to formulating the right modularisation approach (see Figure 7.3). Research stage 1 shows the shortfalls of each of the tools and the modularisation drivers prioritised by the collaborating company. It concludes that each modularisation tool either takes into consideration a small subset of modular considerations (i.e. DSM or GVI) or lacks a robust approach for data analysis (i.e. MIM). As modularisation in construction requires the need to address multiple drivers, research stage 2 investigates a systematic multi-driver approach to modularisation.

A case study was carried out to address a multi-driver modularisation problem. Three modularisation drivers were addressed, which cover technical specification, manufacturing and common unit. The order in which they were addressed reflects the priority determined by the collaborating company. Multiple modularisation tools were used in the research, which includes design structure matrixes (DSM), generational variety indexes (GVI), coupling indexes (CI) and cost weightings (CW). The modularisation research was conducted on the same plantroom product. The methodology of the study involves: i) data collection for the product case to be studied;

ii) selection of the modularisation drivers; iii) application of the tools to fulfil the three modularisation drivers; and iv) integration of the outcomes from the tools to satisfy the three modularisation drivers.

Data Collection. Product data and knowledge were acquired through document analysis and a reverse engineering methodology as described in research stage 1.

Selection of the modularisation drivers. The modularisation drivers were prioritised based on the preferences of the collaborating company, as explored in research stage 1.

The application of the tools to address the modularisation drivers cover the following:

- Design Structure Matrix (DSM): the DSM model developed in research stage 1 was utilised to address the technical specification modularisation driver.
- Design Structure Matrix (DSM): a second component-based “function” DSM model was developed to address the manufacturing modularisation driver. Four pieces of information were used to build the model. These information covers physical connection, machining commonality, functional dependency and assembly sequencing. The data and information to build the model was collected from CAD drawings, product manuals, product schematics and assembly animation models.
- An adapted version of Martin and Ishii methodology was implemented for addressing the common unit modularisation driver (Martin and Ishii 2002). Specifically, a cost weighting element was added to determine the importance of each component to component relationship. By combining GVI, Coupling Index (CI), and Cost Weightings (CW), it is now possible to determine the relative cost impact of redesign of one product component on the overall product. The generation of the GVI, CI, and CW is presented below.

Generational Variance Index (GVI): The GVI was generated though a modified QFD model (Wee et al. 2017b) and calculated by summing up the potential redesign work as a result of changes in the product requirements. The information necessary to generate this matrix was collected from interviews with engineers from the collaborating company.

Coupling Index (CI): A coupling matrix was developed using the methods proposed in Martin and Ishii (2002). The coupling matrix was used for the identification of the degree of coupling between two product components. The matrix generates two types of coupling indexes. The first, known as “coupling index supply” (CI-S), establishes the level of design information supplied to a component. The second, known as “coupling index received” (CI-R), details the level of design information received by a component. Information for the matrix was collected from CAD files and supported by information gathered through reverse engineering.

Cost Weightings (CW): Cost weightings were determined by the prices obtained on the basis of possible online purchases. The actual cost of the plantroom product was not used due to information sensitivity. CW was used to illustrate the potential value of costing as an improvement to the traditional common unit method described in Martin and Ishii (2002).

The application of GVI and CI for the development of modular platforms follows the method developed by Martin and Ishii (2002). It is desirable to standardise as much of the product as possible in the form of a product platform, which incurs very few changes across product generations. Components of the product that cannot be completely standardised will have to be modularised. Full standardisation should be considered for components that are expected to have no change across product generations. Full modularisation should be considered for components that will need to be modified to meet expected customer requirements without requiring other components to change.

Integration of the outcomes. The design resulting from the technical specification driver was compared against that of the manufacturing driver. The design highlights commonality between the two drivers. The design was then adapted to include that of the common unit driver, which are non-conflicting with the two previous drivers.

7.3. Evaluation of the modularisation tools

This section of the research presents the results of the application and evaluation of the three modularisation tools (i.e. Dependency Structure Matrixes, Modular Identification Matrix, Generational Variety Index).

7.3.1. Dependency Structure Matrix

Dependency Structure Matrix (DSM) addresses technical specification as a modularisation driver. It also considers maintenance issues but not robustly, as it looks at spatial preferences only. DSM clusters product sub-systems based on their dependencies (see Figure 7.5). High dependency amongst product sub-systems means that the sub-systems have high functional reliance on each other. Therefore, it would be beneficial if they were clustered together into a module. This would allow the module to hold a section of the product functionality and address the technical specification.

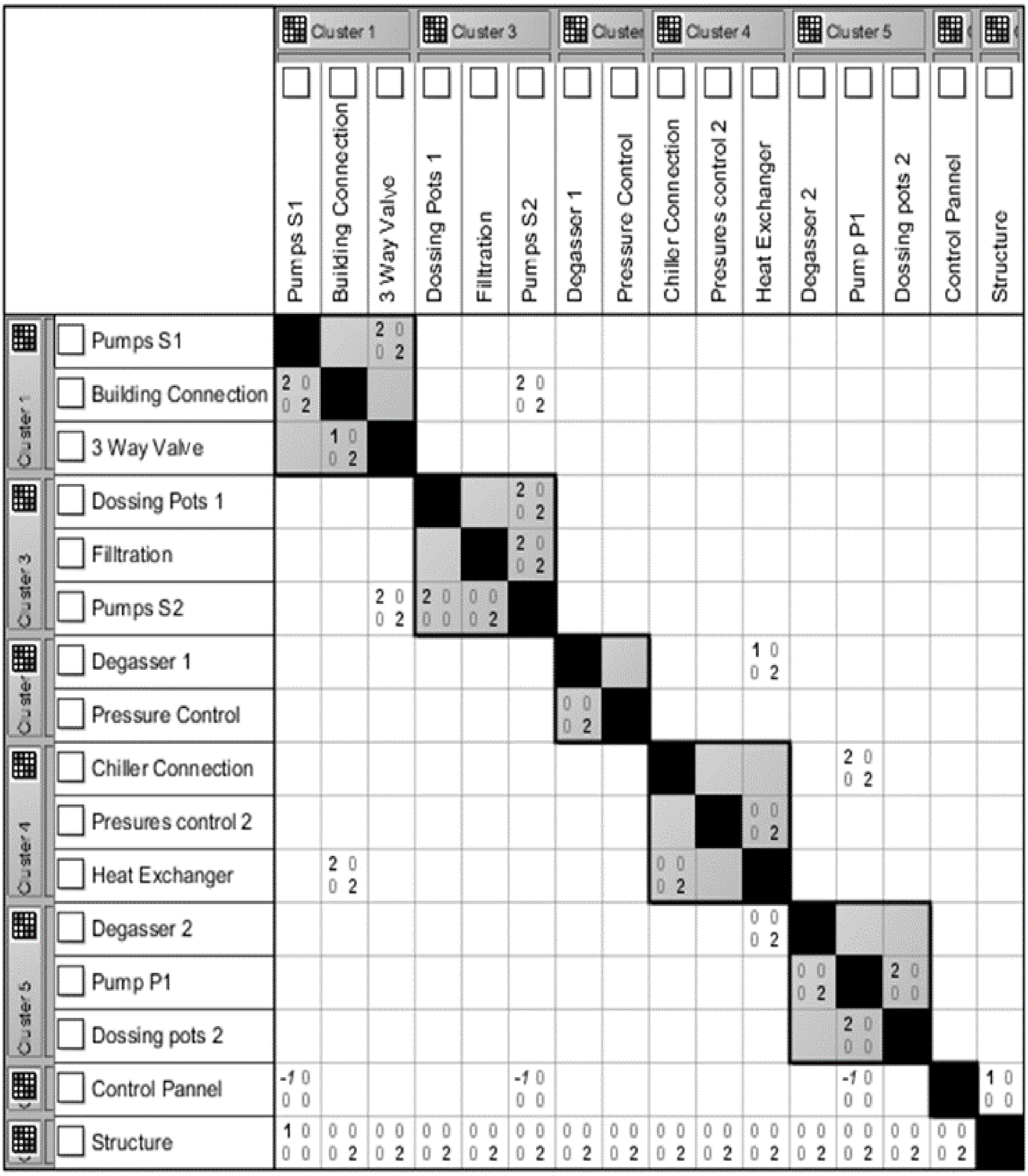


Figure 7.5. Dependency Structure Matrix

The DSM model was built using a total of 16 product sub-systems, which were mapped on to themselves capturing the plantroom's material flows and spatial preferences (see Figure 7.5). Sub-system to sub-system dependencies were labelled on a scale of 2 to -2, where 2 signifies a required dependency and -2 implies a detrimental relation. The material flows were established from the product mechanical schematic. The spatial preference is based on safety, operational and maintenance considerations. The CAM clustering algorithm was used to cluster sub-systems into modules based on the input dependencies. The partitioning feature was then used to determine the ordering of the modules. As can be seen in Figure 7.5, seven modules (indicated as clusters) were recommended by the DSM tool with two modules, which consists of a single product sub-system (i.e. control panel and structure).

Of the seven modules, five main modules (i.e. those composed by at least two product sub-systems) are highlighted in the product schematic in Figure 7.6.

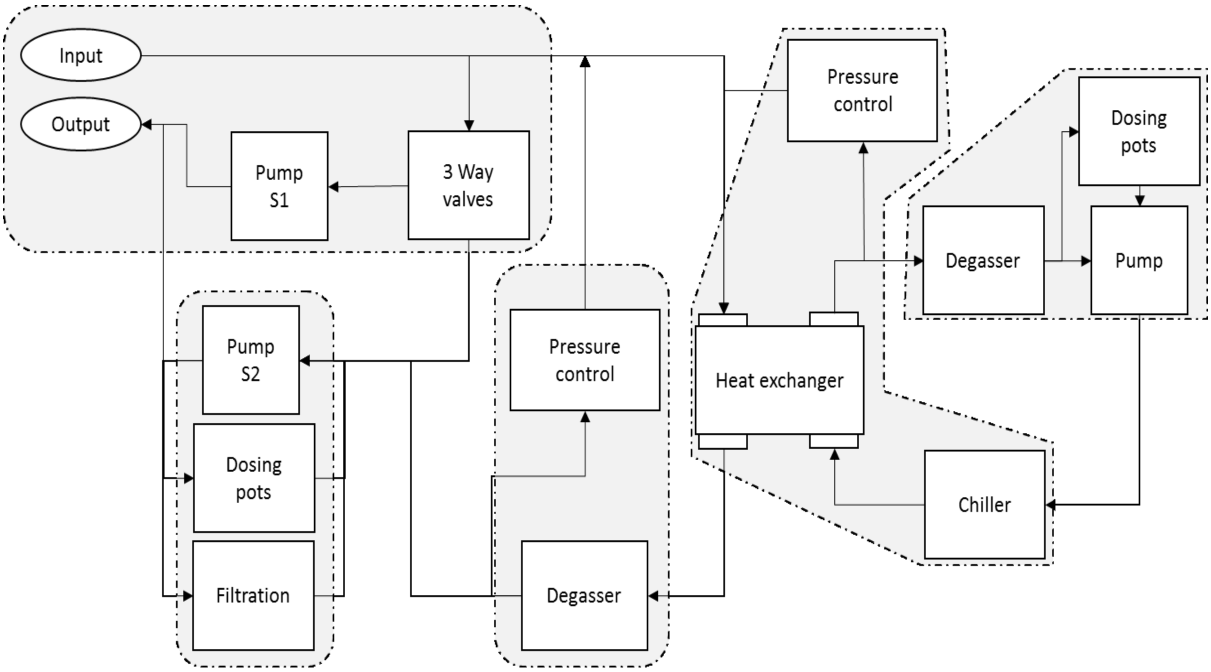


Figure 7.6. Clustering for DSM (technical specification modularisation driver)

7.3.2. Modular Identification Matrix

Modular Identification Matrix (MIM) has a more holistic approach to modularity and supports as many modularisation drivers as a user wants. It also offers a platform for determining how the various modularisation drivers interact with each another. The MIM tool was applied to map 15 modularisation drivers against the 16 product sub-systems (see Figure 7.7).

Modularisation drivers are defined by Erixon (1996) and Hölttä-Otto and Borjesson (2010), who identified twelve original modularisation drivers. The drivers are *technical specification*, *styling*, *carry over*, *product planning*, *technology push*, *production/organisation*, *common unit*, *separate testing*, *purchasing*, *maintenance*, *product upgrading* and *recycling*. In this research, *production or organisation* has been broken down into *production process* and *manufacturing*, where *production process* focusses on factory operations and assembly sequences, while *manufacturing* looks at strategic restrictions on the product due to technical manufacturing issues such as equipment and handling constraints.

Two construction specific modularisation drivers were also identified that is *transportation* and *architecture*. These two drivers were determined through a questionnaire and interviews with expert engineers at the collaborating company as explained in Section 7.2.1. The transportation modularisation driver refers to a modularisation force, which may be developed a module to support transportability issues (e.g. geometric or handling concerns). The architecture modularisation driver refers to a modularisation force, which may be developed as a module to support architectural needs determined by the overall building system (e.g. architectural and structural requirements).

Modular drivers	Imp	Building connection	Pump S1	Degasser 1	Dosing-pots 1	Pump S2	3 Way-valves	Filtration	Pressure control 1	Chiller connection	Pump P1	Dosing pots P1	Heat exchanger	Degasser P1	Pressure control P1	Control panel	Structure
Technical specification	9		9			9					9		9				
Styling	1															9	
Carry over	3	9	3			3	3	3		9	3		3	3	3	9	
Product planning	9		1			1					1						9
Technology push	3		1	1		1	1	9	1	1	1			1	1		
Production process	3		9			9					9						
Common unit	9	1	3	3	3	3	3	3	3	1	3	3				9	9
Manufacturing	9																9
Separate testability	3		1	1	1	1	1	1			1	1	1	1	1	1	
Purchasing	1			9	9			9				9	9	9			
Maintenance	9		3	9	9	3		9	9		3	9		9	9	9	
Product upgrading	1							9								9	
Recycling	3		3	3		3		9			3		9				
Transportation	9																9
Architectural	9	9								9							
	Grades	117	195	132	120	195	42	192	111	120	195	120	129	105	96	210	324
Note: imp = importance	M	M1	M1	M1	M1	M2	M2	M3	M3	M4	M4	M4	M5	M5	M5	M6	M7

Figure 7.7. Modularisation Identification Matrix

The tool identifies which modularisation drivers would influence different product sub-systems. In column 1 of Figure 7, each modularisation driver is weighted, depending on its importance. The weightings proposed in Figure 7.7 were assigned in collaboration with the collaborating company. The cells of the MIM tool in Figure 7.7 display a weighting if a driver influences a sub-system. The modularisation driver importance (I) and influence (R) weightings are on a skewed scale, which favours more pressing modularisation drivers. This approach allows easier identification of stronger driving forces (Erixon 1996). The values of the skewed scale are 9 (high importance), 3 (medium importance), and 1 (some importance). From the data, it is possible to determine which product sub-systems best satisfy the modularisation drivers and therefore should form modular nucleuses. Modularisation driver satisfaction grades (MSG) can be calculated as highlighted in equation (1).

$$MSG_x = \sum_{i=1}^{n} \mathrm{I}_i \times R_i \qquad (1)$$

It sums the product of the modular driver importance (I) and influence" (R), where ‘x’ is the product sub-system number associated with the MSG value and ‘i’ is the row number associated with the specific product sub-system. Product sub-systems with higher MSG grades are identified as modular nucleus. The modular nucleuses are Pumps S1, Pumps S2, Chiller pumps, Filtration, Control panel and Structure, with MSGs of 195, 195, 195, 192, 210 and 324 respectively. The remaining product sub-systems are clustered around these modular nucleuses based on engineering judgement and rationale. The nucleuses are marked in grey in Figure 7.7. The three product sub-systems in black stripes in Figure 7.7 have been clustered using rationale based on satisfaction of the common unit modularisation driver, as these are considered to be an optional feature to the plantroom product.

As shown in Figure 7.7, the MIM model has also yielded seven modules. Six modules are based on clusters around a nucleus and one on a common unit rationale. Figure 7.8 provides a visual representation of these clusters on the product mechanical schematic.

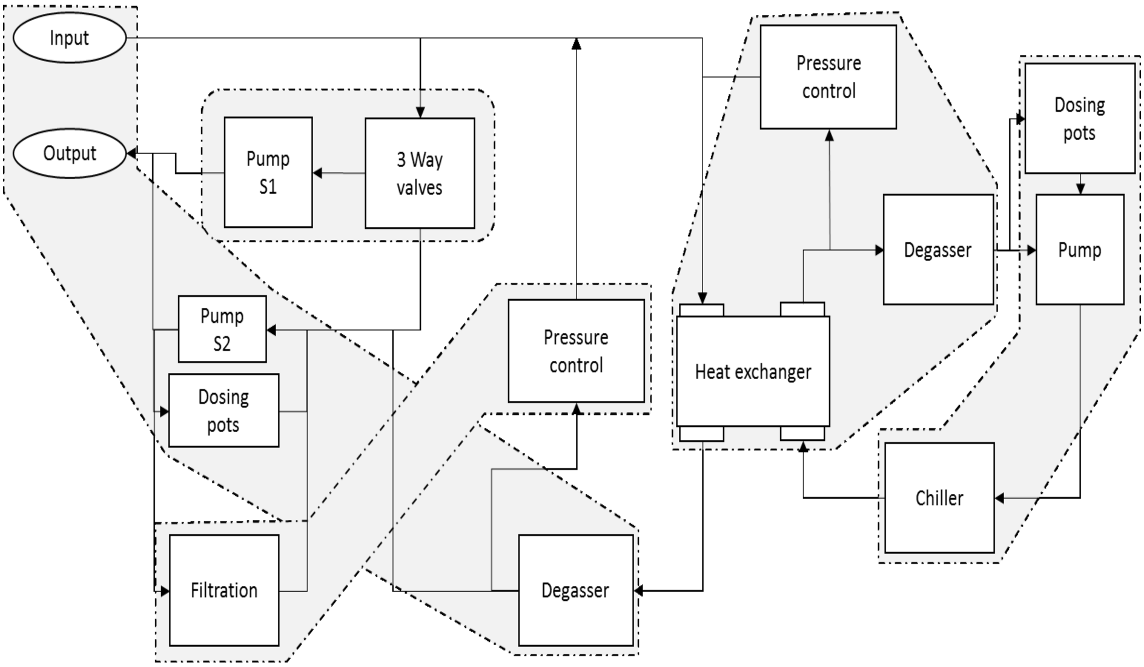


Figure 7.8. Clustering for MIM

7.3.3. Generational Variance Index

Generational Variance Index (GVI) is a metric tool that approximates the likelihood and potential rework needed for the next product evolution. It directly targets technology evolution as a modularisation driver. GVI can be used as a standardisation indicator as well as to address common unit as a modularisation driver. The development of a common unit relates to clustering the product sub-systems, which are least likely to change. As such, it supports the development of a product platform.

In this research the GVI model was generated through a modified version of a QFD 2 matrix for the plantroom (Wee et al. 2017a). Figure 7.9 illustrates the general layout and features of the model. Figure 7.10 is the QFD 2 model used to generate GVI. The matrix maps functional requirements against product sub-systems in regards to the amount of redesign needed if the functional requirements are to change. GVI is traditionally calculated by equation (2) (Simpson et al. 2012) but in this case study it was calculated by equation (3). The new method to calculate the GVI allows for a more comprehensive insight into determining the risk of redesign by summing the product of the change likelihood (C) and the redesign due to change (R), where 'x' is the product sub-system number associated with the GVI value and ‘i’ is the row number associated with the specific functional requirement.

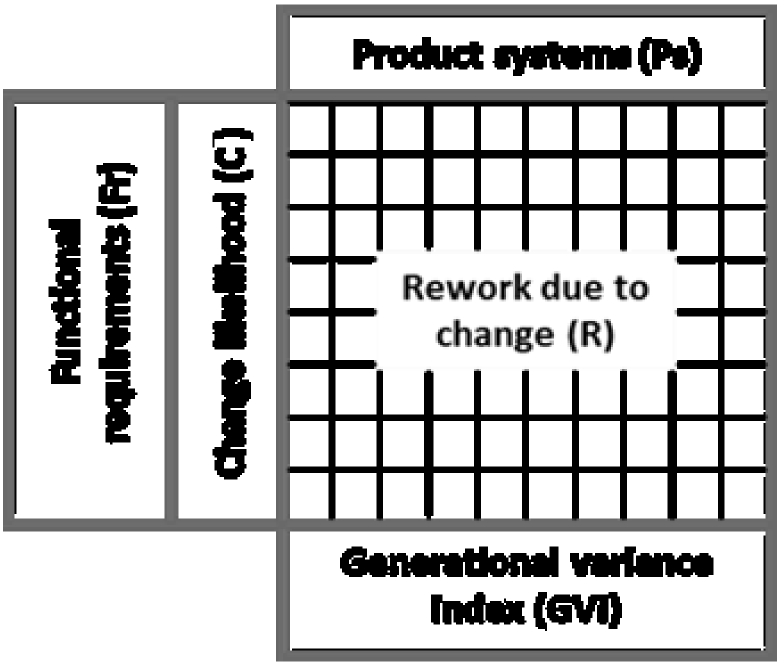


Figure 7.9. Quality Function Deployment Matrix 2

$$GVI_{x\,(Traditional)} = \sum_{i=1}^{n} R_i \tag{2}$$

$$GVI_{x\,(New)} = \sum_{i=1}^{n} (C_i \times R_i) \tag{3}$$

		Product systems (deliverables)		Secondary system (delivery)						Primary system (chiller)					Heat exchanger system	Interface	Cleanning systems	Electronics		Structure	Piping system	
		Product systems (deliverables)		3 Way-valves	VT pump set	Dosing-pots 1	CT pump set	Degasser 1	Pressure control 1	Primary pumping system	Chiller connections	Dosing pots 2	Pressure control 2	Degasser 2	Heat exchanger	Interface	Filtration	User interface	Sensors and wiring	Structure	Piping system	
			Change likelihood	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	**Count**
Primary functions	Deliver cool water	In-take water	9		9		9															162
		Cool water	1	3							0				9							12
		Supply chilled water	1		9		9															18
	Control water temperature	Control water temperature	3	3							0				9							36
	Control water pressure	Depressurize water	1						9				9						0			18
	Control water flow	Control delivery water flow	9		9		9											1	9			252
		Control chiller water flow	9							9								1	9			171
	Monitor plantroom operating conditions	Sense operating conditions	1																3			3
		Prevent instabilities	1		1		1			1									3			6
		Maintain operating limits	1		1		1			1									3			6
		Communicate with user (interface)	3															3	3			18
Secondary functions	Protect plantroom from damage	Prevent accidental impact damage	9																	3		27
		Protect system against freezing damage	1																		1	1
		Protect system from electrical damage	1																3			3
		Protect from pressure damage	1						3				3									6
		Protect system from corrosion	1			1		1				1		1			3					7
	Ensure product integrity	Maintain seal system integrity	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1				3	17
		Maintain cooling systems integrity	1	3											3				1			7
		Maintain water distribution capability	1		3		3									1			1			8
		Maintain systems pressurisation capability	1						3				3									6
	Clean water	Filter impurities and waste	3														3					9
		De-gas water	3					3						3								18
	House components	Support plantroom spines	3																	3		9
		Support module frames	3																	3		9
		Support plantroom components	3																	3		9
		Location of spine mounts	3																	3		9
		Secure internal piping	9													1				3	3	63
	Ensure system compatibility	Ensure system plantroom alignment capability	3													3				3		18
		Secure plantroom module within building	9													1				3		36
			GVI	16	177	2	177	11	16	84	1	2	16	11	40	29	13	27	185	126	31	

Figure 7.10. QFD 2 model used to generate GVI

The GVI values for the plantroom are shown in Table 7.1. A high GVI value signifies that the product sub-system is likely to require redesign work. A low GVI value means that the product sub-system is less likely to require redesign work and is more suitable for standardisation. Therefore, product sub-systems with lower GVI values could be clustered to form a module platform such as the sub-systems in modules 2 and 3 (M#2 and M#3). As shown in Table 7.1, developing a modular product platform using GVI has yielded seven modules. Figure 7.11 provides a visual representation of these clustering on the product mechanical schematic.

Table 7.1. GVI values and module numbers

Product Sub-System	GVI	M#	Product Sub-System	GVI	M#
Chiller connection	1	3	3 Way-valves	9	3
Dosing pots P1	2	3	Control panel	10	6
Dosing pots S1	2	2	Pumps P1	12	5
Degasser P1	6	3	Building connection	14	1
Degasser S1	6	3	Heat exchanger	18	4
Filtration	7	2	Pump S1	26	1
Pressure control P1	8	3	Pump S2	26	1
Pressure control S1	8	3	Structure	40	7

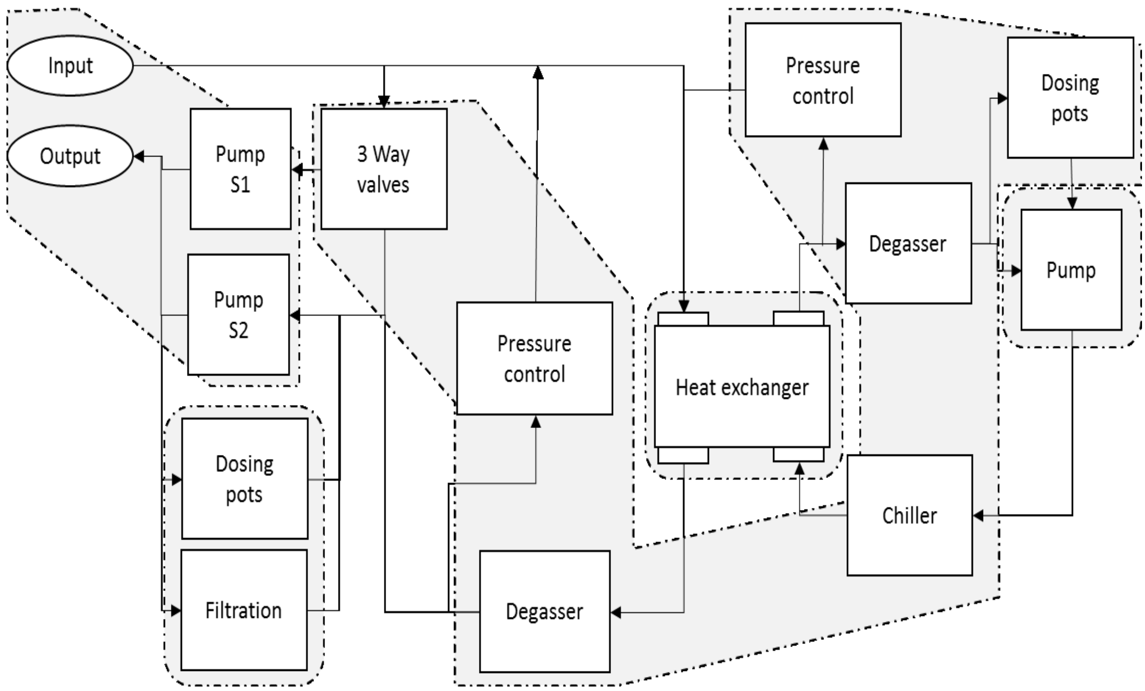


Figure 7.11. Clustering for GVI

7.3.4. Evaluation

The implementation of the three tools resulted many modular designs. Table 7.2 shows the modular designs obtained through DSM, MIM and GVI as well as the modularised reference model proposed by the collaborating company. The reference model was developed through iterative discussions with engineers in the collaborating company. Sub-system to sub-system relationships (SSR) were used to evaluate the three designs by comparing them to the company's reference model. The number of identical SSR within a distinct module indicates the degree of similarity between the result of a modular tool and the reference model. The design with the highest number of identical SSR to the reference model is deemed closer to the design put forward by the collaborating company. The results from this investigation indicate that the MIM based design has 10 out of 13 SSR identical to the reference model, DSM has 5 and GVI has only 3. This evaluation suggests that the MIM based design is distinctively closer to the company design compared to those produced with DSM and GVI.

Table 7.2. Modular plantroom designs

	3 Way-valves	Pump S1	Dosing-pots S1	Pump S2	Degasser 1	Pressure control S1	Pump P1	Chiller connections	Dosing pots P1	Pressure control P1	Degasser P1	Heat exchanger	Building connection	Filtration	Control panel	Structure
DSM	1	1	2	2	3	3	5	4	5	4	5	4	1	2	6	7
MIM	2	2	1	1	1	3	5	5	5	4	4	4	1	3	6	7
GVI	3	1	2	1	3	3	5	3	3	3	3	4	2	5	6	7
Ref	2	2	1	1	1	3	4	4	4	5	5	4	1	3	6	-

The three modular plantroom designs were also ranked by two engineers from the collaborating company in terms of functional dependency between sub-systems (i.e. technical specification). Less consideration was given to the other modularisation drivers because the two engineers primarily focussed on product functionally. Product functionality is the main criteria driving the design of plantroom products. The design produced through DSM and MIM were ranked first and second followed by that produced through GVI. DSM and MIM yielded agreeable results from the perspective of the plantroom design engineering team. In particular, the DSM result was found to be the closest to the modularisation mindset of the participating engineers. This is because the approach to modularisation of the design engineering team is based on product functionality. These views highlight that functionally dependent sub-systems should be clustered together and other influencing considerations are of secondary importance. These views on functional dependence are in line with how the DSM tool operates. While MIM addresses functional considerations, it does not address functionality as comprehensively as DSM. It lacks technical rigor and relies heavily on judgment in determining modules. In addition, MIM also takes on other modularisation drivers. Further, GVI does not address functional considerations at all and is therefore regarded as less relevant for the purpose of designing functional plantrooms.

The three tools approach modularisation from different perspectives and each addresses a set of modularisation drivers (see Table 7.3). The fifteen modularisation drivers in table 7.3 are prioritised according to their relevance to the collaborating company's operations for plantrooms. This prioritisation helps determine the relevance of each modularisation driver against the company's objectives. In addition, a distinction has been made to indicate if a tool can help achieve a modular solution through an algorithmic (A) or a judgment-based process (J).

Table 7.3. Tools fulfilment of modularisation drivers

	Modularisation driver	Importance	D S M	G V I	M I M
1	Technical specification	6	A		J
2	Styling	2			J
3	Carry over	4			J
4	Product planning	5			J
5	Technology push	4		A	J
6	Production process	4			J
7	Common unit	6		A	J
8	Manufacturing	6			J
9	Separate testing	4			J
10	Purchasing	3			J
11	Maintenance	5	J		J
12	Product upgrading	3			J
13	Recycling	4			J
14	Transportation	5			J
15	Architectural	6			J

Notes: A = Algorithmic process; J = Judgement-based process.

A few lessons can be discerned from the evaluation. Firstly, each modularisation tool addresses a different set of modularisation drivers. Secondly, each tool produces a modular solution either algorithmic or judgement-based. Thirdly, there is a need for an algorithmic multi-driver approach to modularisation. Fourthly, there is a need to include more modularisation information (e.g. coupling indexes and costing).

7.4. A multi-driver approach to modularisation

This section of the research presents the results of research stage 2, which address the multi-driver modularisation problem present in construction as covered in research stage 1. In order to solve a multi-driver modularisation problem, it is paramount that a solution can be provided for each modularisation driver. The modularisation solution can then be integrated into a single solution based on prioritisation, which forms the structure of a multi-driver modularisation approach. When the modularisation drivers are addressed simultaneously they provide an integrated approach. This research proposes a modularisation approach, which consists of the following steps: i) research to identify drivers, ii) prioritise drivers, iii) select objectives, iv) select tools, v) run modularisation, and vi) integrate outcomes.

The top three modularisation drivers selected for this research stage are: technical specification, manufacturing and the common unit. Understanding the nature of modularisation drivers can support a reliable selection of modularisation tools. The technical specification and manufacturing modularisation drivers were tackled using DSM. The common unit modularisation driver was tackled with indexes. The technical specification DSM and the GVI models developed in research stage 1 were reused in this research stage. New models for the coupling index (CI), cost weightings (CW) and manufacturing DSM were developed.

7.4.1. Technical specification-led modularisation

This modularisation driver aims at providing the technical specification of a product system on the basis of functional variance (Erixon 1998; and Borjesson 2010). This can be analysed by investigating sub-systems to sub-systems dependencies. High dependency amongst product sub-systems means that the sub-systems have high functional reliance on each other. Therefore, it would be beneficial if they were clustered together into a module. A DSM model was developed for this (see Section 7.3.1).

7.4.2. Manufacturing-led modularisation

The objective of this modularisation driver is to support ease of manufacturing. This can be analysed by investigating operational dependencies. Similar to the technical specification modularisation driver, it would be beneficial to cluster components with high manufacturing operation dependencies.

The DSM model was built using a total of 27 product components (see Figure 7.12), which were mapped on to themselves based on consideration of physical connections, machine requirements, functional dependencies, and assembly sequencing. Component-to-component dependencies were labelled on a scale of 2 to -2, where 2 signifies a required dependency and -2 implies a detrimental relation. Components were clustered into modules based on input dependencies criteria. The partitioning feature was then used to determine the ordering of the modules. Based on these considerations, the DSM model provides a modular solution. Figure 7.13 illustrates the results on the product schematic, where the 27 product components were mapped on to their core modules.

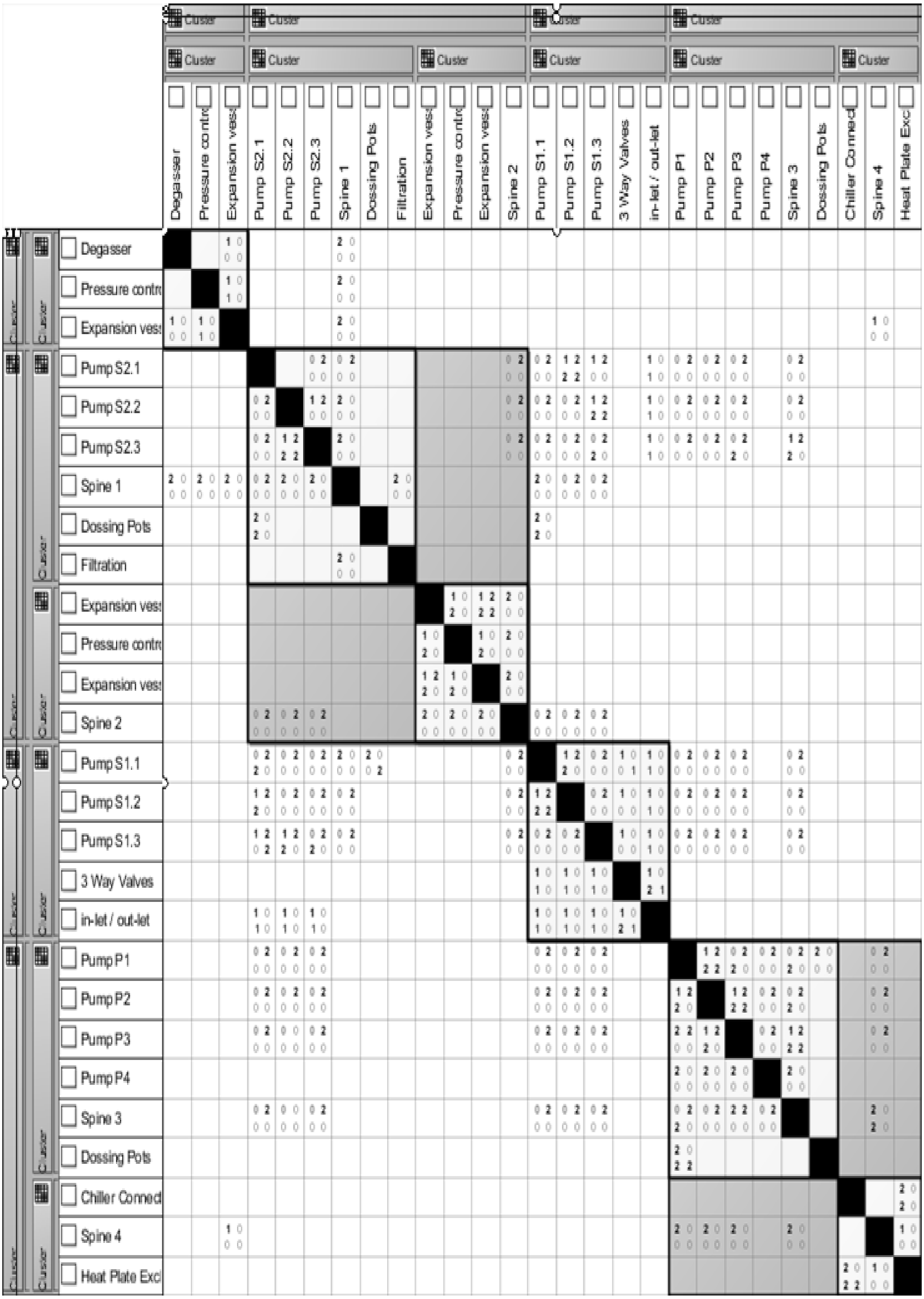


Figure 7.12. Dependency Structure Matrix (Manufacturing)

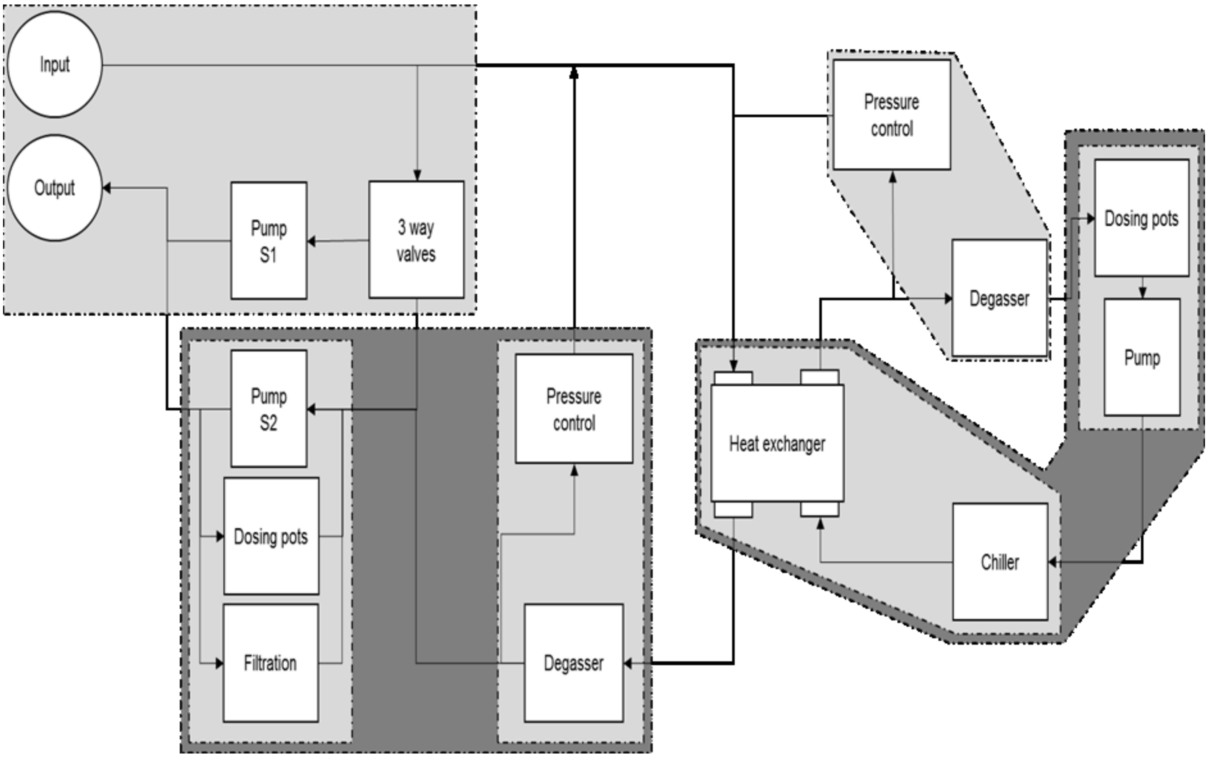


Figure 7.13. Clustering for the manufacturing modularisation driver

7.4.3. Common unit-led modularisation

This modularisation driver clusters product sub-systems which are more likely to change from one product generation to another. It can be used for the identification of sub-systems, which are ideal for standardisation and in turn for the development of a product platform.

A QFD model was developed to generate the GVI, which is a metric tool that approximates the likelihood and potential rework needed for the next product evolution. A coupling matrix (see Figure 7.14) was developed to generate CI, a metric tool that indicates the level of coupling that is present between two product sub-systems. From this matrix, the coupling index supply (CI-S) and the coupling index received (CI-R) can be extracted. Both the QFD-GVI matrix and the coupling matrix were built using a total of 15 product sub-systems. Cost weightings (CW) were also included to determine the importance of each sub-system to sub-system relationship. The resulting GVI, CI-S, CI-R and CW are illustrated in Table 7.4.

		Secondary system (delivery)						Primary system (chiller)					Heat exchanger system	Interface	Cleaning systems	Electronics	Structure	
		3 Way-valves	VT pump set	Dosing-pots 1	CT pump set	Degasser 1	Pressure control 1	Primary pumping system	Chiller connections	Dosing pots 2	Pressure control 2	Degasser 2	Heat exchanger	Interface	Filtration	User interface	Structure	CI -Supply
Secondary system (delivery)	3 Way-valves		2											1			9	12
	VT pump set	10											9	9				28
	Dosing-pots 1							1									9	10
	CT pump set	18		27									9	9	18		9	90
	Degasser 1						1	1									9	11
	Pressure control 1																9	9
Primary system (chiller)	Primary pumping system								18	27		10	9				9	73
	Chiller connections							1									9	10
	Dosing pots 2								1									1
	Pressure control 2																9	9
	Degasser 2																9	9
Heat exchanger system	Heat exchanger		10		10	11		9	18		10	10		9			9	96
Interface	Interface	13									2						9	24
Cleaning systems	Filtration				1												9	10
Electronics	User interface																9	9
Structure	Structure	1	1		1	1	1	1	1		1	1	1	1	1	1		13
	CI- Receive	42	11	27	12	12	2	13	38	27	13	21	28	28	19	1	108	

Figure 7.14. Coupling Matrix

From the data in Table 7.4, specific characteristics of each product sub-systems can be determined. Utilising the data in Table 7.5 and the recommendation on which product sub-systems are suitable for full standardisation (FS), or full modularisation (FM), the "common unit" can be identified (see Table 7.5). The new recommendation (New-Rc) represent an adaption of the recommendation (Old-Rc) proposed in Martin and Ishii (2002). Figure 7.15 marks the sub-systems identified for individual full modularisation and standardisation.

Table 7.4. Indexes associated with each component

	CW	GVI	CI-S	CI-R	Old-Rc	(CI-S) x (Cost)	(CI-R) x (Cost)	New-Rc
3 way-valves	7.43	16	12	42	FM	133	1765	FM
VT pump set	59.71	177	28	11	PM	1121	1106	PM
Dosing-pots 1	1	2	10	27	FM	79	1613	FM
CT pump set	59.71	177	90	12	PM	1414	1103	PM
Degasser 1	24.57	11	11	12	FS	118	1159	FS
Pressure control 1	15.43	16	9	2	FS	15	40	FS
Primary pumping system	78.29	84	73	13	PM	1379	1039	PM
Chiller connections	6.57	1	10	38	FM	85	3273	FM
Dosing pots 2	1	2	1	27	FM	8	2115	FM
Pressure control 2	16.29	16	9	13	FS	16	1061	FS
Degasser 2	22.69	11	9	21	FM	23	1837	FM
Heat exchanger	103.14	40	96	28	PM	2839	1883	PM
Interface	6.57	29	24	28	PM	136	2017	FM
Filtration	11.43	13	10	19	FM	71	1086	FS
User interface	28.57	27	9	1	FS	29	29	FS

Notes: FM = Fully modularised; FS = Fully standardised; PM = Partially modularised; PS = Partially standardised.

Table 7.5. Common unit recommendation rules

GVI	Martin and Ishii (2002)		New Index		Recommendation	Abbreviation
	CI-S	CI-R	Cost - CI-S	Cost -CI-R		
Low		Low		Low	Fully standardised	FS
High		High		High	Partially standardised	PS
	Low		Low		Fully modularised	FM
	High		High		Partially modularised	PM

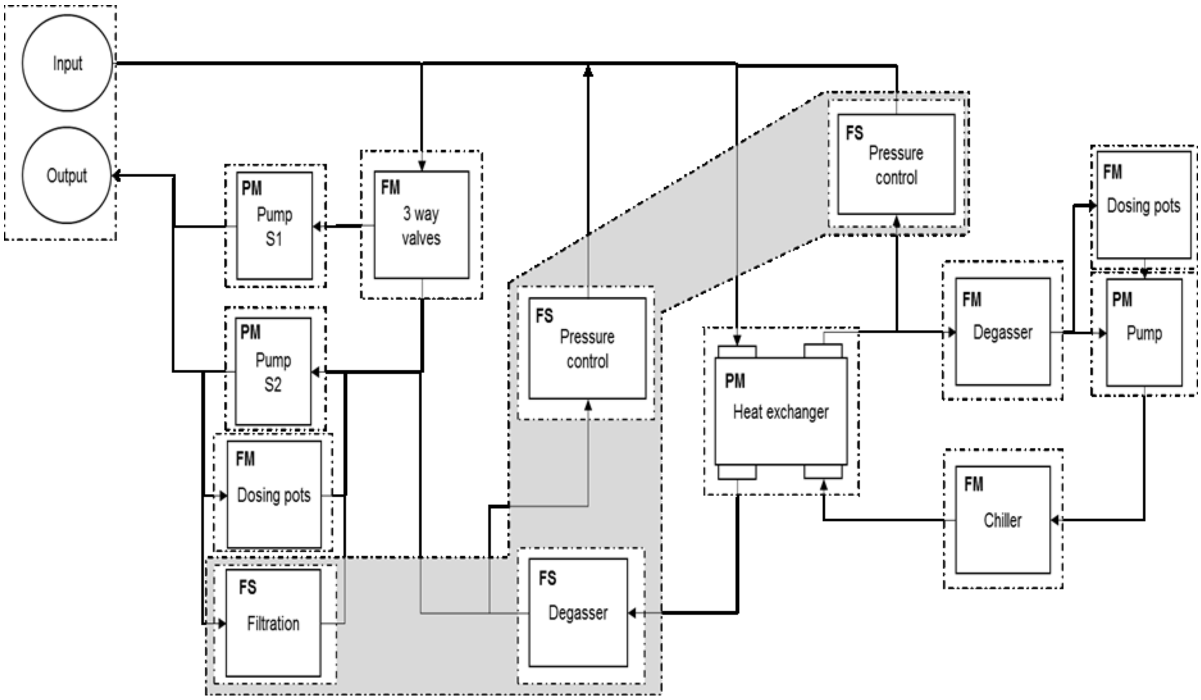


Figure 7.15. Recommendation for standardisation, individual modularisation and common unit

7.4.4. Outcomes of the modularisation for the three drivers and integration

The three modularisation drivers pursued in this research produced different module cluster results (see Figures 7.6, 7.13 and 7.15). By tackling each driver individually, specific modularisation rationales were determined. The integration of the three clusters produced the modularised design as shown in Figure 7.16, where technical specification was prioritised followed by manufacturing and common unit consideration. In comparing the results of the technical specification and manufacturing modularisation drivers, modules 1, 2 and 3 (marked in light grey in Figure 7.16) were identified as non-conflicting modules. It must be stressed that module 3 is also recommended by the common unit modularisation driver. Further comparison of the results of the technical specification and manufacturing modularisation drivers also led to the identification of modules 5 and 6 (marked in light grey in Figure 7.16) as non-conflicting modules. These two modules match those recommended by the manufacturing modularisation driver (see Figure 7.13), which represents a subset of the recommendations from the technical specification modularisation driver (see Figure 7.6). Two sub-systems (i.e. pressure control and degasser) were left floating with possible cluster “a” and “b” since there was no strong rationale to cluster them (see Figure 7.16). Finally, modules 2 and 3 and modules 5 and 6 were further modularised into modules 4 and 7 respectively. This high-level modularisation is recommended by the manufacturing modularisation driver and does not conflict with the recommendation from the other drivers.

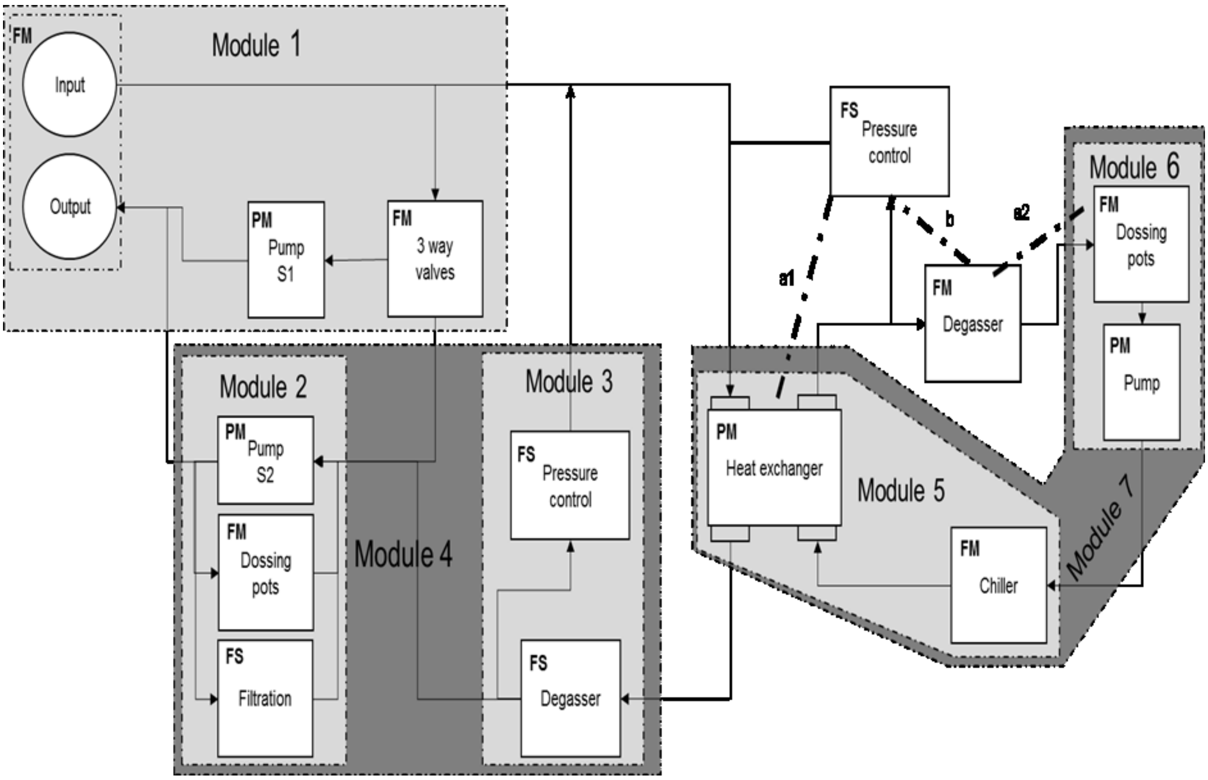


Figure 7.16. Integration of modularisation results

7.5. Discussion

This research shows how modularisation tools can be applied to support modularisation of building service products. It provides new insights into the utilisation of modularisation tools, modularisation drivers, and important factors affecting the design and clustering of the sub-systems or components of a product. The insights emerged in this research are described below.

The research first investigates how three popular modularisation tools can be used to support building design processes. The research distinguished the three tools in terms of modularisation drivers tackled and the process used to produce a modular solution, namely algorithmic or judgement-based process. The former refers to the ability of a tool to handle modularisation drivers from a technical perspective, while the latter is associated with subjective consideration.

The modular designs produced through the three tools were first ranked by experts in the collaborating company. The modular solution obtained through the DSM tool was ranked the highest. The designs were further compared against the reference model to determine design effectiveness. The comparison showed that the MIM tool produced the solution that is closer to the modularisation direction currently pursued by the collaborating company. This can be explained as follows. The DSM based solution best satisfies the modularisation objectives directly relevant to the role covered by design engineers in the organisation (i.e. functional dependency between the product sub-systems). On the other hand, the MIM tool allows the best trade-off between multiple modularisation drivers and it takes into account interdisciplinary considerations.

The research further suggests that neither considering multiple modularisation drivers in a subjective way (as in MIM) nor accounting for isolated modularisation drivers in a technical manner (as in DSM and GVI) is an optimal solution. On their own, each of these tools exhibit limitations and the problem of tackling multiple modularisation drivers with a technical solution is not addressed. Multiple tools need to be considered to capture the full complexity of a modularisation problem. The research recommends to focus on the implementation of complementary tools to generate more effective modular solutions. The application of tools such as DSM and GVI should be considered for more robust solution in respect to their individual modularisation drivers.

Following the recommendation to implement several modularisation tools, a multi-driver approach is proposed. It is important to understand how to develop product solutions that address construction specific modularisation drivers. The proposed approach is more advanced than those utilised by Veenstra et al. (2006) and Gilbert et al. (2013) as it addresses several modularisation drivers with a variety of analyses.

Some valuable lessons can be drawn from this research. First, the utilisation of a data driven approach has permitted a more insightful analysis of the design space to support modular products development. It has helped identify possible design advantages by tackling a modularisation driver. For example, the identification of dependency concentration (i.e. technical specification) for ease of design management or the utilisation of indices to address design objectives.

Second, combining the results from the three modularisation drivers (i.e. technical solution, manufacturing, and common unit), a valuable amount of design information can be used to support the development of a modular product. Product functionality, variety, manufacturing and standardisation have all been addressed in a singular solution.

Third, the work conducted for the common unit shows value in determining which components should be individually standardised or modularised. The addition of a cost weighting variable adds a further perspective to the traditional method of determining common units. This information is valuable to minimise the risk of redesign work.

Fourth, not all components are affected by all modularisation drivers (e.g. structural components are not affected by technical specification modularisation driver). Each modularisation driver led to the implementation of different modularisation models to include different product sub-systems or product components. For example, the product structures tend to be primarily affected by the manufacturing modularisation driver and not by technical specification. This is because the product structure components do not directly provide the product function (e.g. deliver water). A key limitation of this research is that it utilises one case study. Future work should cover a variety of additional case studies across a spectrum of construction products. This recommendation will help develop better and more encompassing modularisation strategies for construction.

7.6. Conclusion

Modularisation in construction is a multi-driver problem. A case study involving two research stages has been conducted to tackle this problem. The first research stage compared three modularisation tools applied to a plantroom design. The three tools were evaluated by determining their effectiveness in addressing modularisation drivers. Fifteen modularisation drivers were identified and prioritised. Each of the three tools addresses a different set of modularisation drivers and with a process that is either algorithmic or judgement based. MIM offers a more holistic approach to modularity and supports a wider range of modularisation drivers. However, it lacks technical rigour in determining modules. DSM and GVI provide technical solutions but each of them focuses on specific modularisation drivers, namely DSM on technical specification and GVI on common unit and technology evolution. It is recommended that DSM, MIM and GVI should be used in an integrated manner to tackle multiple modularisation drivers. As such, they would provide a more effective modularisation approach in construction.

The second research stage looked at developing a multi-driver approach to modularisation and integrated the outcomes into one solution. This research provides an approach to tackle multiple modularisation drivers, which is essential to address modularisation problems in construction. In particular, a solution was developed to tackle three selected modularisation drivers (i.e. technical specification, manufacturing and common unit). Each modularisation driver was first addressed individually to generate valuable design information. The results were then integrated to form a singular modularisation solution that accommodates the requirements from all three modularisation drivers.

Chapter 8

Discussion and Conclusion

8.1. Introduction

This chapter discusses the significance and contributions of the research findings and provides the overall conclusions of the PhD research. The chapter explains how the main objectives of the research have been met, the novelty of the research and challenges addressed by the project. Before concluding, the chapter offers areas for future research.

8.2. General discussion and summary of main results

This research focused on the development of specific approaches for product planning of manufactured construction products. The research outcomes are useful to aid requirements management, modularisation and complexity management of construction products that are to be produced under advanced manufacturing environments. The study developed, evaluated and used methods for requirements management and modularisation analysis.

A limited number of past studies has applied modular product planning tools or frameworks to construction projects (Veenstra et al. 2006; Gilbert III et al. 2013; and Marchesi et al. 2015). However, these studies employed methods from other research fields that were not specifically adapted for construction (Martin and Ishii 2002; Simpson et al. 2006; Borjesson 2010; Jung and Simpson 2016). The tools and methods proposed in this research take a more systematic approach to address product planning and complexity management in construction. This research provides a comprehensive approach involving advanced tools and methods to analyse requirements and on modularisation.

Development of product planning methods and models

Five studies were conducted to support the research aim. These studies cover the applications of requirements management and modularisation for manufactured construction products . These studies were covered in Chapters 4, 5, 6 and 7. They relate to four work streams, which cover: i) the project management environment of the collaborating company and a framework proposal to support product planning, ii) a QFD model, iii) a HQFD model and iv) a modularisation approach. Chapter 4 sets the stage for work on requirements management and modularisation. Chapters 5, 6 and 7 constitute the main aspects of this research. In particular, Chapters 5 and 6 cover research on two requirements management methods (i.e. the application of QFD and HQFD). Chapter 7 explains a modularisation approach, which consists of applying several modularisation tools. Some of the key features and reasons for using the requirement management methods and modularisation approach are highlighted below.

This research specifically uses a functional approach to QFD to introduce more rigour to analyse requirements as compared with other QFD applications (Veenstra et al. 2006; and Gilbert III et al. 2013). The proposed model supports a deeper understanding and analysis of requirements for a manufactured construction product than those proposed in existing literature (Gilbert III et al. 2013; Marchesi and Ferrarato 2015; and Marchesi and Matt 2017).

A HQFD model was developed and applied to address requirements analysis of a complex modular construction system. It builds upon and extends the work on QFD (which addressed requirements of a single product) to cover multiple domains, multi-levels and multi-segments of a complex construction product (an entire building). The HQFD model provided a platform for traceability and generated further information for data analytics. The model is, therefore, a progression for requirements analysis for manufactured building systems.

A modularisation approach was developed to provide design flexibility. It offers an effective solution to achieve strategic modularisation. The approach was applied to support modularisation of a building product (e.g. plantroom). It provided a new insight into the utilisation of modularisation tools, modularisation drivers, and important factors affecting the design and clustering of the sub-systems or components of the product. It also suggests how to formulate modular solutions by tackling multiple drivers relevant to a specific problem at hand (e.g. technical specification and common unit).

Table 8.1 summarises the five studies conducted and their relationship to the overall thesis objectives. An illustration of how the studies and chapters of the thesis are related can also be seen in Figure 8.1. The figure illustrates how the various QFD models are connected to one another in a multi-level environment. It captures the context of how these models should be used together with modularisation to form a product planning framework.

Table 8.1. Relationship between the various studies and thesis's objectives

Study	What does it do	Relationship to thesis	Research objectives addressed
Study 1: Examination of product design approach and development of a framework	Study 1 provides an overview of the industry context and challenges related to product planning. It explains the research approach and describes the relevance of product planning and complexity management. It proposes a framework for complexity management for a manufactured construction product.	This section of the thesis sets the stage for the subsequent chapters. It provides the context in which the case studies are undertaken and explains why they are relevant to further industrialisation in construction.	Research objective B: Determine the current design and product development approaches used by the collaborating company. Research objective C: Develop a framework for efficient, systematic and flexible design of building systems.
Study 2: Requirements modelling with Quality Function Deployment (QFD)	Study 2 covers requirements management (a subsection of product planning). It focusses on a systematic and comprehensive approach for requirements management and analysis. The study was conducted through the application of a	This was the first step towards addressing requirements management for product planning.	Research objective D: Develop and evaluate the application of QFD as a requirements analysis tool for manufactured construction products.

	QFD model on a plantroom product.		
Study 3: Requirements modelling with Hierarchical Quality Function Deployment (HQFD)	Study 3 advances and build upon the works covered in Study 2. However, Study 3 introduces and addresses the issues of requirements management for more complex products that have multidimensional and multilayer requirements. This was brought about by introducing HQFD model.	This work advances the issue of product planning through requirements management as compared with Study 2. It has an increased level of complexity as compared to Study 2 and is better equipped to handle complex products which are more representative of large construction projects (e.g. an entire apartment building).	Research objective E: Develop a method to manage requirements of a complex manufactured construction product.
Study 4: Evaluation of modularisation tools	Study 4 looks at modularisation, which addresses the issues of complexity management. It addresses complexity management through the strategic clustering of product systems or components. Study 4 evaluates existing tools and methods cover in the literature. These tools and methods are not limited to construction but have been applied in other disciplines. This study determines the suitability of these tools and methods for construction.	This was the first step towards addressing complexity management through modularisation.	Research objective F: Evaluate current methods to support development of efficient modular construction products.
Study 5: Multi-driver modularisation approach	Study 5 builds upon the findings of Study 4. The latter found that a multi-driver modularisation approach was needed for construction.	This work advances the issue of product planning and complexity management through modularisation as compared	Research objective G: Develop a modularisation approach to address multiple

	Study 5 presented a multi-driver approach to modularisation.	with Study 2. It provides a more coherent approach to modularisation.	modularisation drivers in construction.

Figure 8.1 shows that the HQFD model (dotted black line) consists of a set of QFD models that have been structured in accordance to the HQFD structure. It also shows that the example HQFD model used only a subsection of an ideal HQFD of a complete building. Modularisation (blue box) is used together with QFD (red box) to handle complexity management issues through strategic clustering. The QFD and modularisation form the product planning framework (green box), which is explained in Chapter 4. In order to manage product complexity effectively it is recommended that all three sets of models (QFD, HQFD and modularisation) be implemented together.

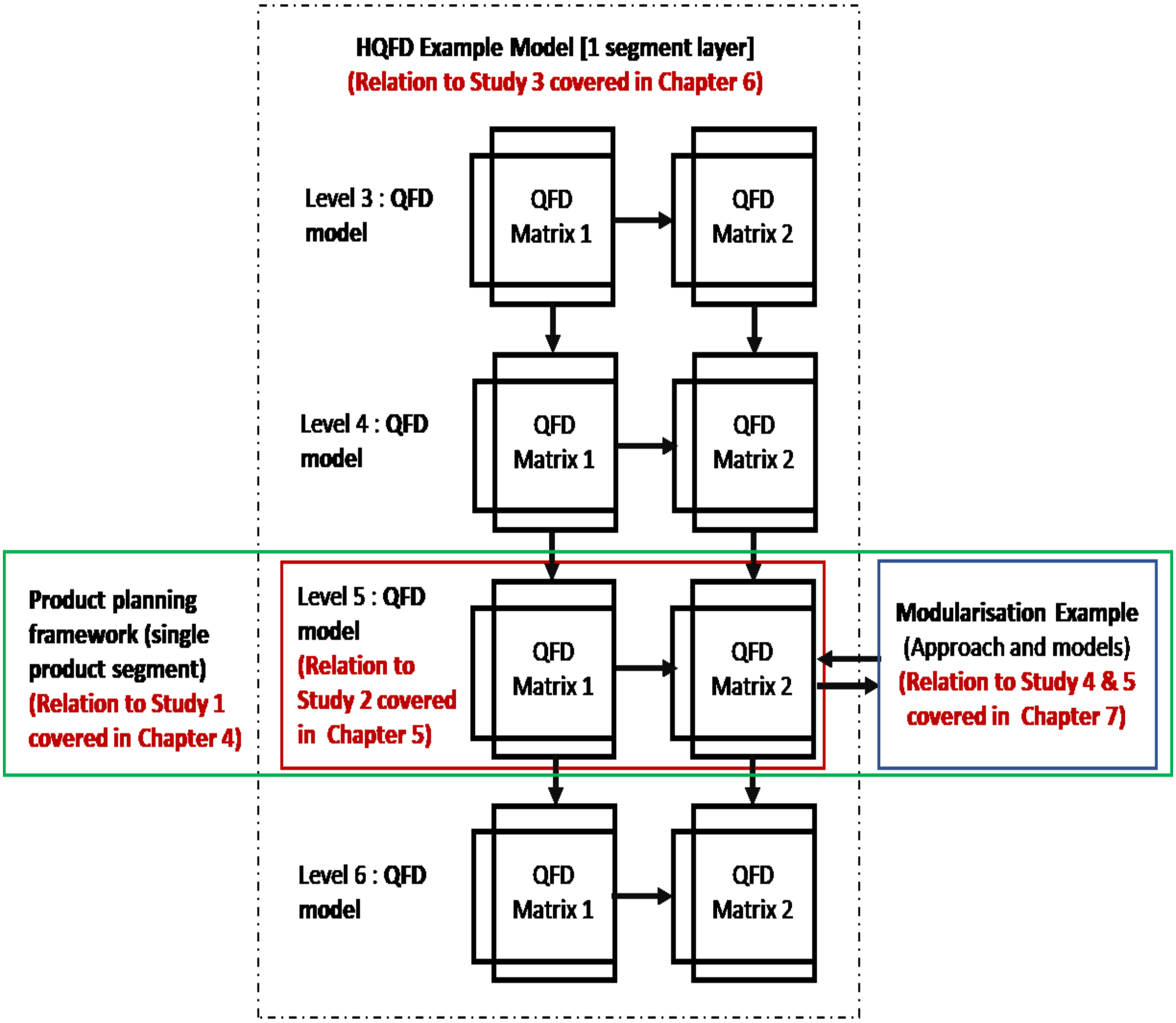


Figure 8.1. Overview of how each study is related to one another

Evaluation criteria

The main evaluation criteria for the tools developed in this research were based on a combination of interviews, surveys, workshops and seminars, which involved various stakeholders (e.g. engineers, experts, consultants) at the collaborating company (see chapter 3). Some specific evaluation criteria included relevance, accuracy, comprehensiveness, product planning support, practicality and usefulness factors. An in-depth evaluation of the models and methods developed in this research was analysed and the results were presented in chapters 5, 6 and 7. An analysis of requirements needed for product planning models were presented in chapter 4 (see table 4.1). The requirements were determined from an initial study of this research that looked at the current design process implemented by the collaborating company. All methods and models in this research provides systematic approach for development of manufactured construction products and are more developed than existing methods described in chapter 4.

Balance between standardisation and product flexibility

There is a need to balance between standardisation (for cost and efficiency reasons) and unique context of a specific system (for flexibility and customisation). There are concerns over a "one size fits all" approach in construction. This is because standardised buildings cannot satisfy all stakeholder's specific needs. This research argues that the entire building or product should not be standardised, but modularised with some modules that can be standardised.

Some level of standardisation is necessary to meet industrial and production goals to increase productivity, lower costs and achieve economies of scale. Standardisation exists in the construction industry, albeit limited to smaller components such as bricks, steel beams, windows and panelled fittings (e.g. walls). In order to increase production efficiency, it is recommended that the level of standardisation be increased as much as possible but without compromising the end users' requirement for product uniqueness.

Standardisation could occur with design methods, production methods, some product modules and some components. This research advocates for standardised systematic design methods (e.g. QFD, HQFD, and Modularisation) that can support implementation of product modularisation and platforms. These methods can increase product flexibility by providing systematic product planning. The product design in construction would need to regulate the degree and composition of standardised product components and methods to ensure customisable results. It is possible to standardised different sections of a building and it's modules separately to achieve a tailored effect.

Role of stakeholders

The main focus of this research is on product planning with a special emphasis on requirements analysis and modularisation. Information for requirements analysis were based on those already determined and collected by project management team, engineers, consultants and experts responsible for the development of residential buildings at the collaborating company.

The models and methods developed in this research are intended to provide a guide and support tools for stakeholders and engineers. This research focuses on industrialisation and production capability, which is based on the perspective of the collaborating company. The research does not take into consideration requirements that are outside of common industrial practices such as user experiences (UX). The requirements collected for this research depended on the expertise, insights and experiences of industrial collaborators (including architects and engineers) as well as consultants to the collaborating company. However, it is recommended that future research could also include UX consideration to enrich requirements and to capture the perspectives of customers. Once the additional requirements have been collected and calibrated, they can then be added to the QFD and product planning model.

This research recommends an additional step in product planning to support stakeholders and engineers in the development of manufactured construction products. The models and methods provide a platform to bring together multiple stakeholders' perspectives. They can be used by stakeholders to form an integrated solution, with the aim to address multi business and industrial objectives. The developed models can guide architects, engineers and other designers to consider a variety of design and stakeholder issues (e.g. sustainability) though it's systematic procedure. Like many product planning tools, the models and methods developed in this thesis are to be used and implemented during the early design stage of product development and as tools to support product planning, decision-making and analytics. These models are intended to support architects and engineers to increase understanding on product requirements and product features. The models facilitate a better understanding of product requirements than existing methods.

This research recommends product planning for the development of product concept and to assist in identifying logic holes. There is a general agreement amongst stakeholders and collaborators of this research that systematic tools (both requirements management and modularisation) are highly valuable for the development of manufactured construction products (see chapters 5 and 7).

Change management influence on models

The models have been developed with the intent to minimise future product changes through more rigorous requirements management and to limit the amount of redesign through modularisation (i.e. only affected modules need to be redesign whilst the rest remain unchanged).

According to the literature, products and systems commonly experience changing requirements and features. It is important to capture complete product requirements at the outset of the product planning stage, so that as little change as possible occurs (Eckert et al. 2012). However, changes can occur, which can result in further redesign (Langer et al. 2012; Morkos et al. 2012; Bauer et al. 2015; and Koh et al. 2015). Therefore is it advantageous to develop engineering products and systems that are adaptable. Several studies have emphasised on the changeability of products (Martin and Ishii 2002; Jiao et al. 2007; Suh et al. 2007; Hu and Cardin 2015; and Koh et al. 2015). Past research have also established that modularity can be used to support product changeability (Baldwin and Clark 2000; Jiao et al. 2007; Saleh et al. 2009; Krause et al. 2013; and Holtta¨-Otto et al. 2013). For example, Ulrich and Eppinger (2012) describe that modular system can support product changes to be made to a few isolated product functional elements without affecting the design of other modules. Modularisation should be carried out during the planning stage of new products.

8.3. Contribution of the study

The aim of this research is to develop product planning methods for complexity management of manufactured construction products. The research objectives supporting the aim can be divided into two key areas. They are to:

1) Develop requirements management tools and methods for product planning (addressed in Chapters 5 and 6) and

2) Develop a modularisation approach for product planning and complexity management (addressed in Chapter 7).

The project has met the above objectives through the development of specific models for requirements management and modularisation of manufactured construction products. Figure 8.2 summarises the key features of the approaches and contributions of the study.

Product planning for manufactured construction products

Research objective	i) To develop requirements management tools and methods for product planning.	ii) To develop a modularisation approach for product planning and complexity management.

Research approach/ model	Requirements management		Modularisation
	Requirements management using QFD model (see Chapter 5).	Hierarchical requirements management (HQFD) model (see Chapter 6).	A data orientated modularisation approach (see Chapter 7).
General features	QFD offers a systematic and data-oriented requirements management and analytics tool. Intended for a single product involving non-detailed considerations (e.g. “deliver water” vs “maximum electrical pump power”).	HQFD offers a systematic and multi-dimension requirements management tool for a complex product (with multiple product segments). Consists of a set of QFD models. Considerations include product domains and multiple product levels (high level to details level).	Offers an approach for strategic clustering of product systems and components in accordance to modularisation drivers.
Specific features	Model is data orientated. Data are hierarchically organised. Information model (non-functional requirements,	Multi-dimensional information model (3 dimensions: product segments, product domains, product levels). Highly structured.	Data orientated model. Matrix and index style tools. Compatible with QFD.

	functional requirements, product systems). Data analysis is possible.	Data rich environment.	

Contribution context			
Technical contribution	Better requirements information management compared to existing practice. Supports further data analytics work.	Better requirements information managements. Better information structure. More detailed and comprehensive analytics than QFD.	More strategic and effective modularisation approaches compared to existing practices.
Product contribution	Better requirement coverage.	Supports better systems analytics for complex manufactured construction products.	Better defined product features in compliance to modularisation drivers.
Management contribution	Enable analysis of requirements management. Fewer iterations and failures during product development. Supports requirement traceability and data analytics. Possible analysis for resource allocation.	Supports complexity management for requirements management. Good for handling complex products. Supports requirement traceability and analytics.	Change management. Risk mitigation. Business strategy through modularisation. Complexity management and control through modularisation.
Literature contribution	Fills the gap by explaining systematic requirements management approaches for manufactured construction products.	Fills the gap by explaining systematic requirements management approaches for complex construction products.	Fills the gap by explaining modularisation approaches in construction.

Figure 8.2. Research objectives and contributions of the study

The novelty of the research lies in the development, integration and application of systematic analytic tools to achieve efficiency and flexibility in production of construction products. The research tackled complexity management by developing and tailoring systems engineering tools (i.e. DSM, GVI, MIM, QFD and HQFD) and integrating them into complexity management approaches for manufactured construction products.

The novelty of the research relates to two major areas: "requirements management" and "modularisation". The former looks at requirements management for complexity management in construction. The significant contribution from this area of work includes: the information model, multi-stakeholder organisation, prioritisation for shortfall identification and Hierarchical Quality Function Deployment. The novelty of the modularisation approach includes the explanation of modularisation problems in construction as well as the introduction and adaptation of modularisation tools from other disciplines.

8.3.1. Requirements management through QFD model

The work on requirements management provided a step forward in attaining systematic tools and abilities for the development of construction products (see Chapter 5 for details). It was conducted through the implementation of the QFD model to a single plantroom product. The QFD model was able to address requirements management in a systematic and structured manner. The model was appropriate to be used for requirements management and product planning of a manufactured construction product (i.e. plantroom).

In developing the QFD model, two QFD matrixes were developed and examined. The application of QFD in advanced off-site construction received positive feedback from the collaborating company's engineers. It was found that the QFD model was useful for a rigorous organisation of non-functional and functional requirements and for documentation of complex relationships between them. The QFD model supported the collaborating company to achieve more advanced requirements documentation and analysis capabilities compared to the existing approach. The model captures engineering experience by allowing the design of next generation products to be less reliant on expert engineers. The prioritisation system is a valuable feature of the QFD model, which was confirmed by the results of the evaluation workshop. It helps identify issues of importance in advanced off-site construction. This feature is crucial for efficient allocation of resources and investments.

The information model used in the QFD application is an adaptation of that described in Burge (2007). The model maps non-functional requirements to functional requirements to product systems. It is more functionally orientated as compared to the traditional information model, which normally is applied to quality function deployment. The model is more in line with functional thinking and functional based modularisation. The model also reflects the multi-stakeholder reality of the construction industry where a multi-stakeholder hierarchy organisation of requirements was added to the QFD model. The model was used also for hierarchical requirements modelling, which relates to requirements analysis for complex systems through the use of hierarchical QFD systems.

The QFD model was useful for data analytics for shortfall identification. Data analytic methodologies can be implemented with QFD. This can be pursued by first identifying which requirements are most important to achieve advanced manufacturing and modular design objectives; and second understanding the current fulfilment shortfall of requirements.

8.3.2. Hierarchical requirements management through HQFD model

The issue of more complex requirements management was addressed further by using a HQFD model (presented in Chapter 6). The model used a set of QFD tools to analyse requirements of an apartment building. The model was developed through multiple QFD matrixes, which cover 5 product levels of an apartment building that involved multi-dimension and multi-level requirements. They included the following product segments: i) apartment building, ii) module apartment, iii) the module frame, iv) interfacing systems, and v) alignment rack. The HQFD model supported a better system structure and a comprehensive analytics environment. In addition, the data rich environment of HQFD supports further exploration into traceability activities and data analytics.

The model also provided an approach to support requirements management for complex products. The findings of the HQFD study (see Chapter 6) include the following:

- The model involved more advanced structure and information management suited for complex systems. HQFD facilitates the handling of complex systems than a single QFD model described in Chapter 5. It does this by providing a more advanced organisational and systematic information structure (including the dimensions of domain, segments and levels).
- HQFD carries all benefits present in QFD with additional synergistic advantages. Some of these advantages include HQFD levels of interconnectivity, which support requirements traceability.
- HQFD provides a data rich environment which is ideal for opportunities for further data analysis: An example was made in this study, which indicates building construction requirements most likely to be affected by a shift towards manufacturing production systems.
- HQFD provides a framework for future development of building systems. The abundance of information available to an engineer can turn HQFD into a potential platform to launch innovation for development of future products.

This research supports that HQFD is a requirements analysis model that can be used to address complexity management of product systems. It tackles requirements analysis from a multi-dimensional context and takes into account multiple requirements such as product segments, product levels and requirement domains. It has the added benefit in providing a better organisational structure for requirements analysis and supports requirements traceability across product levels and product segments. Through the HQFD model, better data analysis and studies can be conducted.

8.3.3. Complexity management with modularisation approach

Modularisation provides a foundation for the development of modular products and can support complexity management (Hölttä-Otto 2005; Ulrich and Eppinger 2008; and Emmatty and Sarmah 2012). This study examines the suitability and context of modularisation tools for construction. The initial work on modularisation evaluated three set of tools by determining their effectiveness in addressing modularisation drivers and their processes (i.e. algorithmic or judgement-based process). Fifteen modularisation drivers were identified and prioritised. Three specific tools (i.e. MIM, DSM, and various indexes) were carefully examined. Each of the three tools addressed a different set of modularisation drivers with a process that is either data oriented or judgement based. The evaluation looked for modularisation drivers and clustering techniques of these three tools. An approach was also developed to address modularisation for multiple modularisation drivers from a data-oriented perspective.

The research distinguished that different modularisation tools tackle different modularisation drivers. The DSM tool was preferred by design engineers at the collaborating company because it focuses on product technical specification, which was more in line with the perspective of these engineers. On the other hand, the MIM tool produced a solution that is closer to the modularisation direction currently pursued by the collaborating company. This was due to MIM's ability to consider multiple modularisation drivers, though limited by higher levels of subjective consideration as compared to DSM. Models for GVI and other index styled tools were developed to address standardisation issues. However, these index tools were not the primary consideration for modulation, despite being deemed as important. The research established that multiple tools need to be considered to capture the full complexity of a modularisation problem in construction. The research recommended to focus on the implementation of complementary tools to generate more effective modular solutions.

The research further emphasized that modularisation problems and drivers must first be understood in order to achieve effective modularisation in construction. It would then lead to a tailored solution to the modularisation problem. The details of the modularisation problems explored in the study are unique to construction and therefore the solution proposed is novel.

Some other lessons can also be drawn from the findings generated by the modularisation model (see Chapter 7). These findings can be summarised as below:

- The utilisation of a data driven approach has permitted a more insightful analysis of the design space to support modular products development.
- Modularisation in construction can be a multi-driver problem and therefore adopt approaches which are able to handle multiple drivers. Chapter 7 provides an example, which addresses three drivers (i.e. technical solutions, manufacturing, and common unit).

- The approach used for product modularisation provides a valuable feature for identifying product component which could be recommended for individual standardisation of modularisation of product subsystems.
- Additional weighting and variable could be highly valuable for tackling modularisation drivers.
- Different modularisation drivers have different characteristics and can affect different product components.
- Future work should explore where modularisation would have the highest impact and on which building segment.

A strategic application of modularisation to address modularisation drivers was made. It resulted in a proposed approach for multi-driver modularisation of construction products (see Study 5, Chapter 7). It utilised and integrated several data-oriented modularisation tools such as DSM and index tools. The approach provided advantages for analysis of data oriented and multi-driver modularisation in construction. It was found to be more detailed and comprehensive than with the application of a single modularisation tool.

8.3.4. Summary of contributions

This research has generated contributions, which are summarised in Table 8.2. The table lists the contributions that this research brings and indicates the major corresponding sources of information that supported the research. In particular, the research has contributed to a better understanding on achieving efficient and flexible manufactured construction products, the need for an effective product planning phase, approaches for development of models, the need to strengthen design engineering processes and the identification of industry strategy.

The research has also provided a valuable step forward in product planning for manufactured construction products. It provided systematic models and approaches to address requirements management analysis and complexity management, which has been lacking in coverage in the literature (Marchesi et al. 2013). The research is more targeted towards the development of products suited for higher levels of construction industrialisation, which has not been well documented.

Table 8.2. A summary of research contributions and benefits

Areas of contributions	Contributions and benefits of the research	Found in study				
		1	2	3	4	5
Research problem context	Addresses requirements management for manufactured construction products.	x	x	x		
	Addresses modularisation for manufactured construction products.	x			x	x
Product planning context	Complements advanced manufacturing activities.	x	x	x	x	x
	Provides a better environment for design engineering decision making.	x	x	x	x	x
	Contributes to a better understanding of product change management.				x	x
	Supports requirements fulfilment of products.	x	x	x		
	Contributes to requirements management and analysis.	x	x	x		
	Contributes towards addressing and handling large amounts of requirements in a structured and systematic manner.			x		
	Addresses complexity management issues.	x		x	x	x
Tools and models	The models developed are data orientated in nature.	x	x	x	x	x
	The implemented tools are comprehensive and have a well-defined structure, which is much needed for the advancement of product development practise.	x	x	x	x	x
	Closes logic holes in design and systems engineering considerations.	x	x	x		x
	Reduces subjective design input in the design process.	x	x	x	x	x
	Increases systematic in the design of engineering information and modelling.	x	x	x	x	x
	Provides additional valuable insight into model analysis.	x	x	x	x	x
	The tools implemented in the study are compatible with other possible tools.	x	x	x	x	x
	The model developed in one-off work. Models are reusable for further product planning.	x	x	x	x	x
Design / systems engineering procedure and industry practice context	Collection of design engineering knowledge and better documentation than current method.	x	x	x		
	Increases streamlining process and ensures a structured approach to product design and development than current method.	x	x		x	x
	Increases systematic properties and rigor in design engineering processes and practices than current method.	x	x	x	x	x

The research indicated that product planning should occur before the start of heavy project work. This will help gauge the level of difficulties, complexity and potential pitfalls within product planning. Specialist teams working on specific section of the building need to develop their own QFDs, which can be quickly compiled or integrated to form the overall HQFD for the apartment building. This is to be followed by modularisation of product systems for further product complexity and change management. Although this research addresses the issue of manufactured product in construction, the approaches used can be easily adapted to other complex products in other industries.

Each requirement analysis or modularisation model is specific to the product and business situation in which it was developed for. However, the models developed in this research are generisable and could be applied to another company that is producing similar products with the same functionality. Therefore, the developed QFD models and their component requirements can be utilised across the industry, except for target values, for similar products of the same functionality. Target values are typically determined by the business strategy of a company. For non-similar products, the application of the models would need to be adapted to reflect new set of requirements and product functionality. This research suggests that the methods for developing models can be applied to develop other models (either for requirement analysis or modularisation), even to products or process outside construction. The result arising from the implementation of these methods will be a systematic and data centric model for management of complex systems.

8.4. Research challenges and limitations

The research has had to deal with several challenges which were overcame over the process of this project. These challenges (see Chapter 4) are discussed below:

(i) **Project complexity:** This research has had to deal with a large spectrum of product and project features. These features are spread across multi-stakeholders, multiple teams and information owners. The fragmentation of information and its provenance from different sources posed a challenge in the research with respect to getting access to coherent information and data.

(ii) **Data collection:** The project complexity has also made data collection difficult. It has often led to the need for extensive networking to identify and access product or project data and experts' feedback. There was also difficulty to determine experts and collaborators for the study.

(iii) **Project case studies:** Advanced manufactured construction product examples are scarce and are being developed or yet to be developed. This has resulted in a limited number of projects to choose from to examine.

(iv) **Live projects and dynamic data sets:** Dealing with live projects involve a dynamic (changing) product definition and requirements. These changes made developing and finalising QFD matrixes challenging.

(v) **Evolutionary products and redesign:** Dealing with live products which were intended to be adaptable to fit changing customer needs presents an issue of having product requirements and information which are unfixed and sometimes ambiguous. The challenge met was the need to have a single set of requirements and product information to conduct research.

There are also other limitations of the project and in the application of the research findings. These limitations are covered below.

First, the research only focussed on product planning stage of project development. Hence, future development would need to include additional related aspects such as product life cycle, customer product features selection and product configurations.

Second, the research scope is limited to the construction industry. Using the models developed in this project in other industries would require caution as there may be industry-specific factors, challenges or data limitation.

Third, there are specific challenges in applying the research findings to product planning, tools development, system engineering and industry-specific strategy contexts as highlighted in Table 8.3.

Table 8.3. Challenges in using the research findings

Limitations	
Research issues	This research addresses product planning in construction with a higher level of complexity and detailed information requirements, which resulted in increased complexity of solutions than those covered in the literature. By examining the issues of product planning with a higher level of details, the complexity level of both the product planning problem and solution increases. This results in more complex product planning approaches than existing ones.
Product planning specific factor	The models developed in this research could increase the complexity in design techniques and practice.
Tools development context	The tools developed were resource intensive. The level of product planning and product systems engineering requires high levels of knowledge on products and their requirements. This knowledge may not be available or are constantly changing.
	The models developed in this research are detail orientated (detail product information, such as product feature and requirements). They require high levels of rigour and diligence in the development and implementation than current practices.
	The development of the models require training. Companies might not have trained staffs to develop the models.
Design / systems engineering procedure and industry practice specific consideration	The models in this research require significant investment of time to develop.
	The addition of product planning tasks can make the design stage of product development longer.
Industry strategy specific factor	Increased product planning and design expenses. Companies may be unwilling to incur in these expenses. It may also conflict with an “action first” corporate culture.

Fourth, additional case studies covering other construction products (e.g. kitchen pods and mechanical electrical plumping systems) would be beneficial to gain a deeper insight into more robust product planning and complexity management.

Fifth, despite the many potential benefits that product modelling can bring to the construction industry, there are barriers to its implementation. Systematic and data-oriented models require the need to gather a comprehensive set of product information and requirements, which may be hard to acquire. For example, this may entail several meetings with stakeholders prior to the development of the models, which may not be a simple task in a business environment. There is also an assumption that the client and the respective stakeholders have complete and unchanging knowledge of the requirements, which may not be the case.

Sixth, once the requirements are comprehensively collected there is the issue of interdisciplinary conflicts when organising and prioritising different requirements, as well as modularisation drivers. There is also the risk of resistance to the adoption of the tool once developed, as it may be viewed to conflict with the traditional culture of flexible operations in the organisation. In order for systematic tools to be used successfully in construction, there is a need to increase support for its utilisation.

The above challenges and limitations would need to be addressed in future research so as to develop suitable complexity management tools and to encourage companies to use them effectively.

8.5. Relation to UN Sustainable Development Goals

The UN Sustainable Development Goals (SDGs) were not specifically and extensively covered in this thesis because they were not the primary focus of the research. However, the study has addressed a few of the SDGs (see table 8.4). In particular, the work has direct relevance to the UN sustainable development goal 9: “industry, innovation and structure”, goal 11: “sustainable cities and communities”, and goal 12: “responsible consumption and production”. This research supports better product planning for further industrialisation in construction, which is in line with SDG goals 9, 11 and 12. The research enables a more effective delivery of advanced building products through requirements management and modularisation. The product planning solution of this study contributes to the industrialisation agenda for the construction industry. It provides an innovative solution to modularisation problems faced in construction.

It is important that the construction industry recognises the growing significance of these global goals and their implications to the industry. In this regard, companies and stakeholders in construction need to address adequately the economic, social and environmental aspects of these goals.

The models developed in this study can be adapted to address other aspects of the SDGs. In particular, future models can be developed to incorporate additional SDG considerations such as clean sanitation, climate adaptation, sustainable infrastructure and buildings, affordable homes and responsible use of resources in construction. In order to further incorporate other sustainable development goals, future product planning models need to factor in additional SDG requirements. The QFD models developed in this research can be adapted to include these additional requirements, including those related to other sustainability targets (e.g. affordable and clean energy, and climate action). Modularisation can also be made more focused on product life cycles and to be made more in line with other SDGs.

Table 8.4. UN Sustainable Development Goals addressed in this thesis and suggestions for future work

SDG No	Title of goal	Description	SDG addressed in this thesis	Further work to support SDG
1	No poverty	End poverty in all its forms everywhere.	No.	Yes. Affordable housing.
6	Clean water and sanitation	Ensure availability and sustainable management of water and sanitation for all.	Not directly. However the construction of buildings involve water delivery systems and sanitation services.	Yes. Examples: improve further efficient water delivery systems and sanitation services.
7	Affordable and clean energy	Ensure access to affordable, reliable, sustainable and modern energy for all.	Not directly. However the construction of buildings involve delivery of energy to users.	Yes. Examples: smart energy systems and solar panels.
8	Decent work and economic growth	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all.	Not directly. Industrialisation in construction contributes to economic development. This thesis addresses industrialisation in construction.	Yes. Need to take into account employment impact, and new skills requirement and training.
9	Industry, innovation and infrastructure	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation.	Yes. This research proposes industrialisation in construction and innovation in building infrastructure.	Yes, through mass-customisation in construction.
11	Sustainable cities and communities	Make cities and human settlements inclusive, safe, resilient and sustainable.	Yes. This research covers development of buildings through product planning.	Yes. Smart buildings and smart cities.
12	Responsible consumption and production	Ensure sustainable consumption and production patterns.	Yes, through effective requirements management, and efficient use of resources including reduction in redesign.	Yes. Future research could look into approaches to increase responsible production in construction.
13	Climate action	Take urgent action to combat climate change and its impacts.	No.	Yes. Future work could incorporate green building requirements and carbon neutral construction industrialisation.
17	Partnership to achieve the goal	Strengthen the means of implementation and revitalize the global partnership for sustainable development.	Not directly.	Yes. Construction industry can play an important role in the global partnership through sharing experiences in developing environmentally friendly buildings.

8.6. Future research

This research has made specific contributions to the field of systems engineering, product planning and complexity management in construction in areas such as data analytics, information management and model development. It provides a platform for future work in product planning and development and contributes towards the industrialisation agenda in construction.

The research suggests that future work in product planning for manufactured building systems would need to utilise more systematic tools for planning and information modelling. As a result of this research, future work should examine the following specific issues:

- **Further features:** The requirements management and modularisation model developed so far could benefit from additional features. For example, the QFD model covered in Chapter 5 does not include all known features of the tool. Hence, future requirements management and modularisation models would need to capture requirements trade-offs and employ the concepts of prioritisation theories, weighting normalisation, and cost drivers. Further development of requirements management and modularisation approaches for the construction industry would need to give careful consideration to business competitive factors (e.g. cost reduction) and the benefits of automated off-site construction.
- **Further data analytics:** Data analytics can be used for studies to identify potential for increased product design efficiencies or flexibility. It can also be used to target business objectives and control decision making trade-offs.
- **Targeted modularisation:** As recommended earlier, future studies could be conducted to explore which building segments would benefit most from modularisation activities.
- **Automated data harvesting:** Data collection was one of the most difficult hurdles to overcome in this research. Future work involving automated data harvesting would reduce the demand on resources required to build QFD, HQFD and modularisation models. The development of an automated data harvesting process would be most welcomed in future work. However, a lot of the information on construction project tends to be fragmented and scattered across several teams

and in various information forms. This will require significant data clearing and processing or a standardised method to support digitalised information capture.

- **Expansion on other product development areas:** This research focussed on the product planning stage of project development only. Future development could include additional related aspects such as product life cycle management, customer product features selection, and product configuration models. They could be developed as add-on models to the HQFD model developed in this study.
- **Expansion into risk management:** While this research has addressed product risk management (Chapter 7 on modularisation), it would be beneficial to further develop the models to handle more advanced risk management strategies to support the overall business objectives and decision making.
- **Protocol developments**: As models and approaches developed in this research are fairly complicated and require training, it may be useful to develop protocols to aid in the development of future model.
- **Product planning framework for production operations:** In order to effectively achieve further industrialisation and mass-customisation in construction, a product planning framework should be developed for production operations. When the product planning framework for a single product and a product planning framework for a production operation are paired together they can provide a framework for high level of mass-customisation. Such product planning framework could contribute to achieving efficiency and flexibility across both product and production operations.

8.7. Conclusion

This research has met its objectives to develop and apply product planning methods for manufactured construction products, involving system engineering approaches or analytical tools to requirements management and modularisation. It has taken a systematic and comprehensive approach in the examination and application of analytical tools and models. Specifically, the research has led to the development of models that are able to support effective product planning and complexity management.

Three specific methods (i.e. QFD, HQFD and modularisation) stood out to be effective in meeting the research objectives. The novelty of this research can be divided into two major work streams: "requirements management" and "modularisation". The contribution to the requirements management work included a systematic approach through the application of QFD model and hierarchical requirements management with the use of HQFD model and data analytics. The modularisation work covered the explanation of modularisation problems in construction, adaptation of modularisation tools from other disciplines to construction and formulation of a multi-driver modularisation approach.

The research was supported with five studies, which generated the following contributions:

- It recommended a framework for product planning and complexity management (outcome of Study 1: explained in Chapter 4). In particular, it recommended that requirements management and modularisation should be addressed simultaneously so that high levels of and flexible product requirements can be effectively obtained. The framework is effective in handling single product requirements, modularisation and complexity management.
- The research developed a systematic and comprehensive model through QFD approach for requirements management under a single product situation (outcome of Study 2: explained in Chapter 5). The model can support systematic and data-oriented analysis for manufactured construction products.
- In addressing requirements management for complex and multiple products, the research developed a hierarchical requirements model through HQFD (outcome of Study 3: explained in Chapter 6). The model accommodated a better structure and organisation of requirements that involve multi-dimensions, which in turn contributed to traceability and data analytics. The model can support a better management of complex product requirements that involve multi-layer or a composite of sub-products (product segments) of a building.
- The research further evaluated the capabilities of existing modularisation tools and their potential for application to construction. An integrated multi-driver modularisation approach was applied in complexity management through strategic component clustering. The model encompasses a combination of modularisation tools to address product change management, product complexity management,

and mass-customisation problem faced in the construction industry. The approach was able to identify modularisation drivers and generated modularisation solutions (outcome of Study 4 and 5: explained in Chapter 7).

This research established that both the QFD and HQFD models present valuable instruments for data analysis. While the former can be applied to requirements involving a single product, the latter extends the QFD model and benefits to analyse multi-dimension requirements (from a single construction product to an entire composite building). The research has also illustrated that QFD can be used to gain insight into design influence for manufacturing in construction.

The HQFD model supports a deeper understanding of advanced off-site construction requirements. This is the first application of a HQFD model to a modular construction scenario. Past applications of construction requirements analysis were limited to applications of QFD to mainly buildings or construction operations. HQFD maps requirements not just on a single product level but for an overall product system that consists of multiple products or segments and multiple levels resembling a complex system. This research has contributed to the development of systematic tools for management of complex construction products, involving multi-dimension and interconnection of multilayer consideration. It has provided a valuable step forward for product planning of manufactured construction products.

The application of modularisation approaches for manufactured construction products has been limited. This is because most existing works focus on optimisation of construction operations instead of on manufactured construction products. Therefore, this research has provided a platform for modularisation approaches that could support future manufacturing ambitions in construction. The proposed approach highlights the rationale of modularisation drivers which can support broader business strategy and objectives.

While the models developed in this research are specifically for manufactured construction products, they could also be applied to non-construction industries for complexity management and product planning. However, the limitations of this project need to be taken into account and the models need to be adapted to fit the specific industry consideration, including on data challenges. This research has also contributed to the knowledge body in explaining systematic and comprehensive methods to address requirements management and modularisation, which has been lacking in the literature. The proposed models or approaches used in this research contribute to a deeper understanding of product planning for complexity management in construction than those proposed in existing literature (Veenstra et al. 2006; and Gilbert III et al. 2013).

Other outcome of this research is the proposed complexity management approach and single product framework, which integrates the various models and tools to address complexity management. The product planning framework integrates requirements management models and modularisation approach for planning of flexible manufactured construction products. It provides a more comprehensive understanding of the functionality of construction products for manufacturing.

This research has provided a stepping stone towards understanding and developing effective tools and models for flexible construction products to support product planning in the industry. The outcome of this research is valuable for companies to address product change management, higher levels of industrialisation and even to target the state of mass-customisation. However, to maximise on potential product planning benefits further studies need to be conducted focussing on industrial needs and operations.

8.8. Publications

The following peer reviewed conference papers were published during this research:

1. ***A Product Planning Framework for Mass-Customisation in Construction.***
   Wee, T.P.Y., and Aurisicchio, M. (2018). In Proceedings of the 15th International Design Conference (DESIGN 2018). Dubrovnik, Croatia (pp. 917-928).

2. ***Modularisation for Construction: A Data Driven Strategy***.
   Wee, T.P.Y., and Aurisicchio, M. (2018). DS 91: Proceedings of NordDesign 2018, Linköping, Sweden, 14th–17th August 2018.

3. ***Evaluating Modularisation Tools in Construction***.
   Wee, T.P.Y., Aurisicchio, M. and Starzyk, I., (2017). Proceedings of the 34rd ISARC International Symposium on Automation and Robotics in Construction, Vol. 34, Taipei, Taiwan, IAARC, pp. 325-332**.**

4. ***The Application of Quality Functional Deployment to Modular Off-site Construction Products*****.**
   Wee, T.P.Y., Aurisicchio, M., and Starzyk, I. (2017). In DS 87-4 Proceedings of the 21st International Conference on Engineering Design (ICED 17) Vol 4: Design Methods and Tools, Vancouver, Canada.

5. ***A Systems Engineering Framework for Mass Customization in Construction*****.**
   Wee, T.P.Y. and Aurisicchio, M. (2017). In MCPC World Mass Customization and Personalization Conference, Aachen, Germany.

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Appendix 1: QFD questionnaire

Circle relevant option and/or provide comments for questions 1-9.

1. The **"Non-functional"** requirements

The non-functional requirements are **relevant**

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

The non-functional requirements are **accurate**

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

The non-functional requirements are a **comprehensive** set

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

Comments

2. The **“Functional”** requirements

The functional requirements are **relevant**

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

The functional requirements are **accurate**

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

The functional requirements are a **comprehensive** set

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

Comments

3. State any **requirements not captured** in the QFD tool

4. The **relationships**

The relationships between non-functional and functional requirements are **relevant**

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

The relationships between non-functional and functional requirements are **accurate**

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

Comments

5. The QFD tool is **practical** to implement

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

Comments

6. The QFD tool can support **engineering planning**

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

Comments

7. The QFD tool can support **engineering design**

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

Comments

8. **QFD** and the current “**Requirements Document**”.

A product specific approach to requirements documentation is more useful than one focused on multiple products.

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

Categorisation of requirements into non-functional and functional is more useful than no-categorisation.

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

Organisation of requirements with a structured method (QFD matrix) is more useful than a text-based report.

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

9. Additional comments

Name: --(optional)

Position in LOR: ---

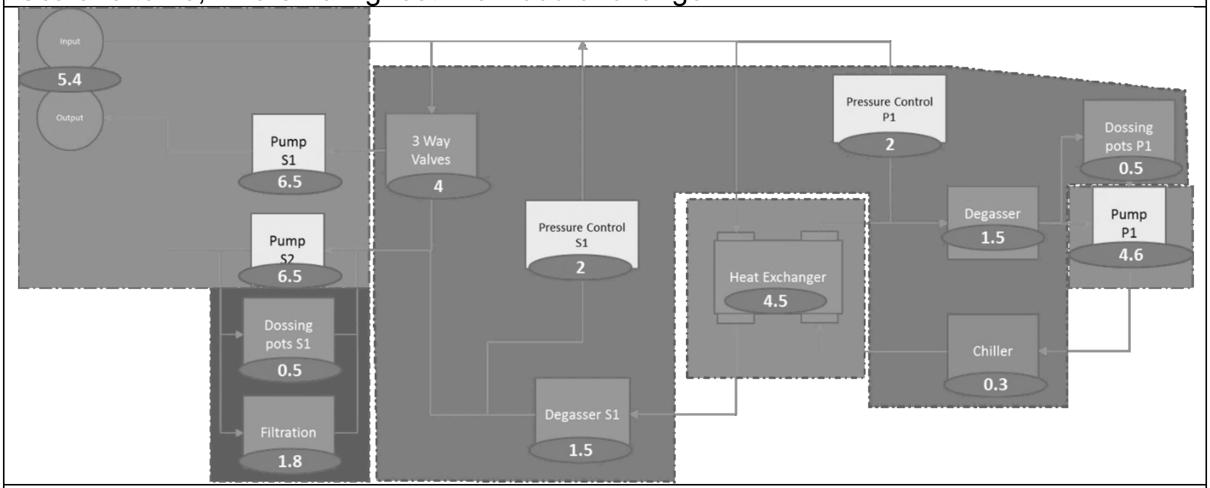
Department/group in LOR: ---

Appendix 2: Modular configuration questionnaire

Name: ________________________________

This questionnaire includes modularisation results collected from the application of three different modularisation tools. Each modularisation result recommends modules from clustering of the same 14 product systems. These product systems exclude 2 product systems (structure and the control panel).

Modular Configuration 1:
Note: Numbers signify likelihood for change, given a change in product requirements.
Scale: 0 to 10, where 10 highest likelihood of change.



1) Is this configurations useful?

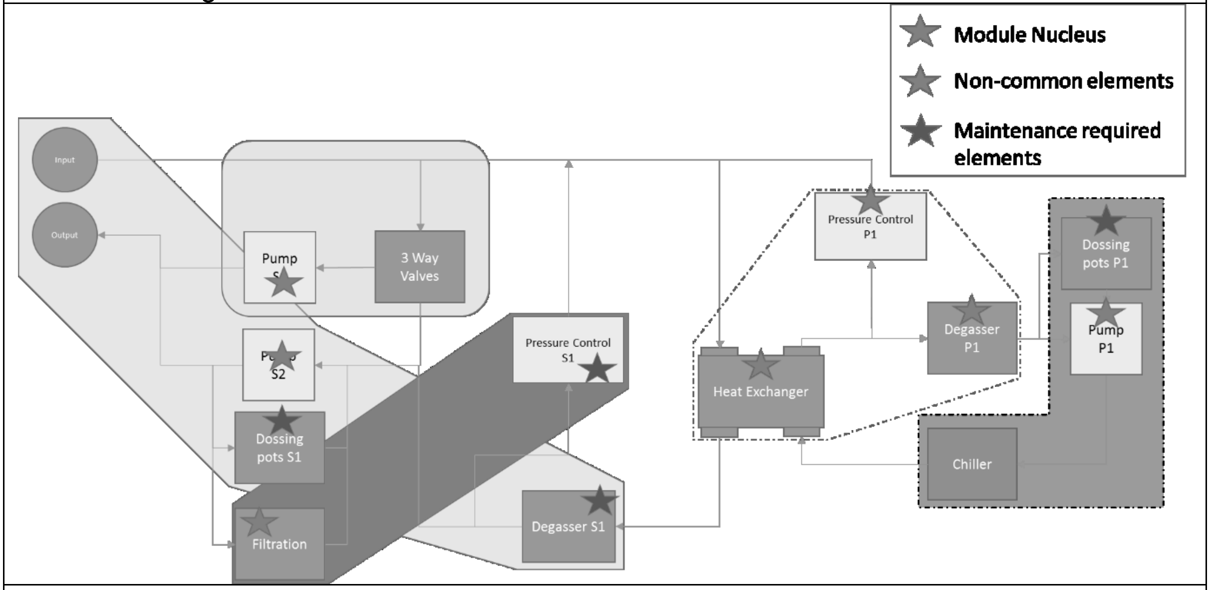
Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

2) What are the advantages?

3) What are the short falls?

Additonal Comment:

Modular Configuration 2:



4) Is this configuration useful?

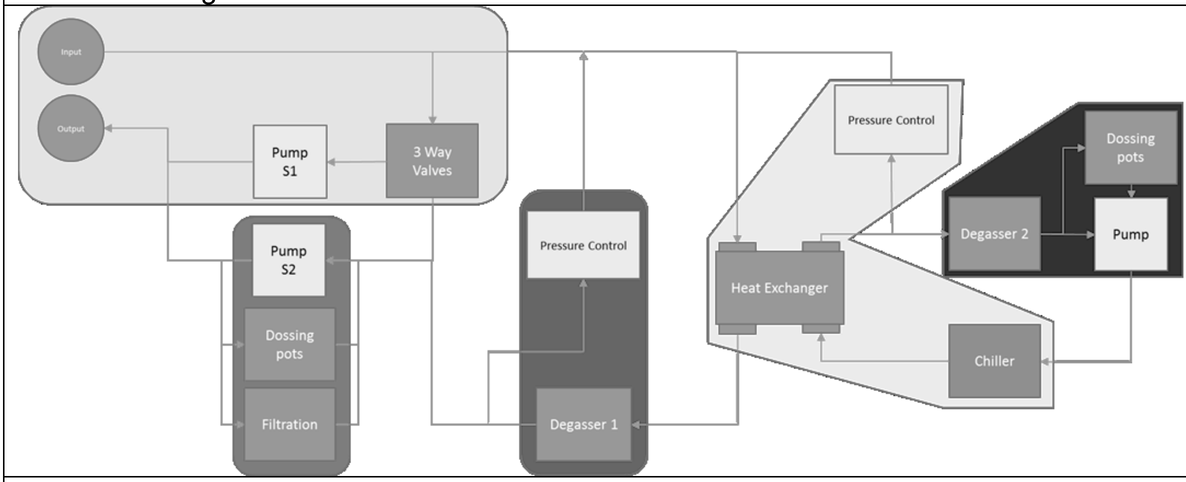
Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

5) What are the advantages?

6) What are the short falls?

Additonal comment:

Modular Configuration 3:



1) Does this configuration captures adequate engieering considerations for modularisation?

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

2) Is this relevent and useful product modularisation?

Strongly Agree	Agree	Neither	Disagree	Strongly Disagree

3) What are the advantages?

4) What are the short falls?

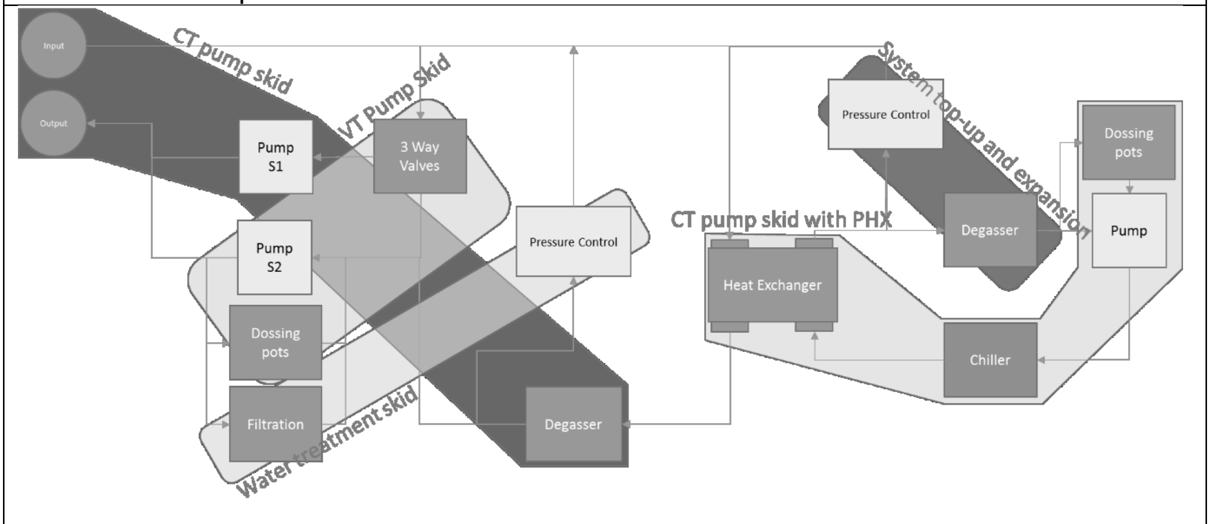
Additonal comment:

Rank the modular configuration

Based on your engineering knowledge and expertise which modular configuration best satisfies your product consideration?

	Rank from 1 to 3 (where 1 is the highest)
Modular configuration 1	
Modular configuration 2	
Modular configuration 3	

LOR Current Proposal



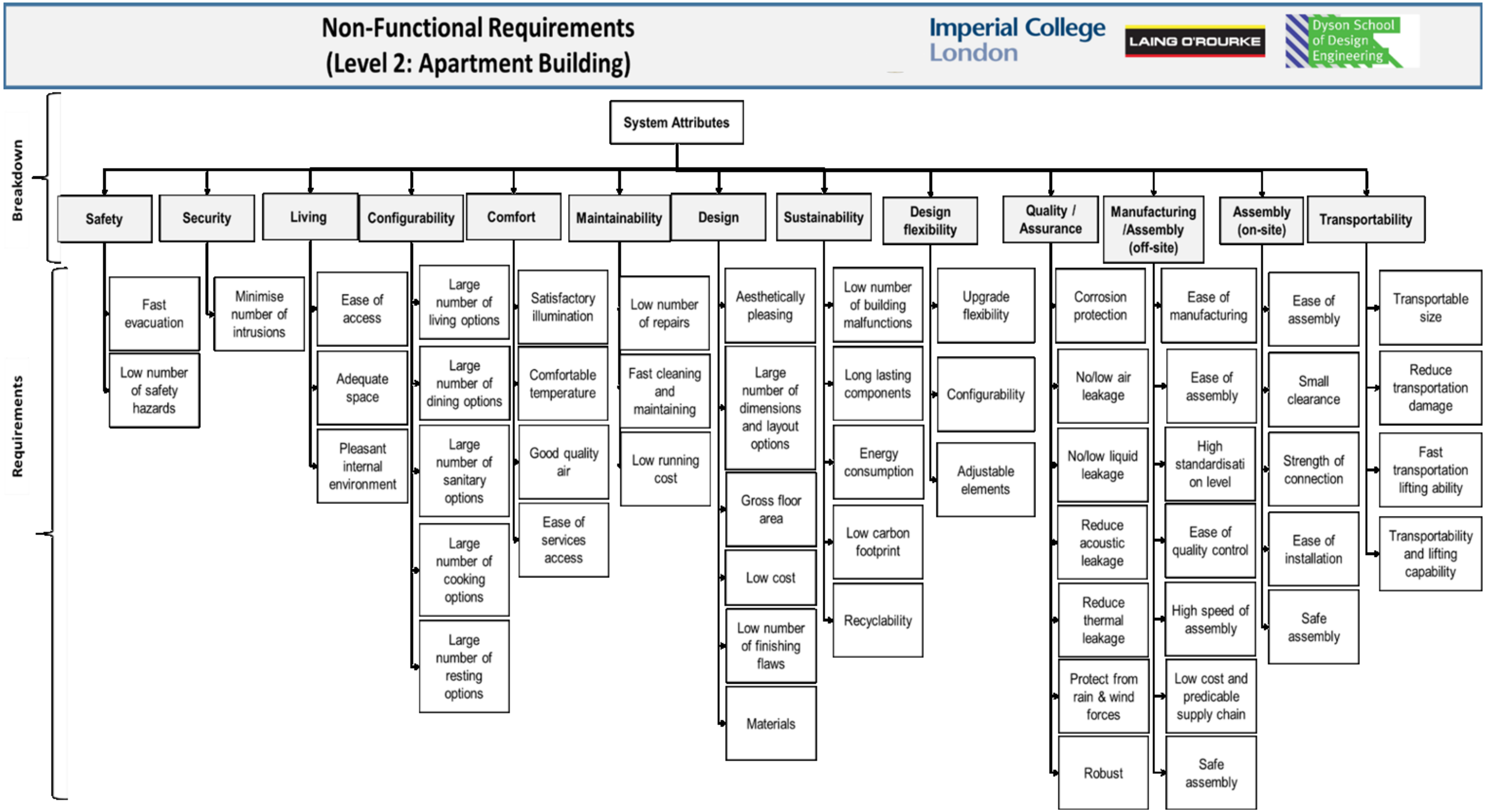
Modular Drivers Questionnaire

Modified from Gunnar Erixon's MFD questionnaire for modular construction

	Modular Drivers		Importance rating (Scale of 1 to 5)
1	Technical specification		
	Can this subsystem carry the product's technical specification verification?	[ ] Many [ ] Some [ ] Non	
2	Styling		
	Is this subsystem influenced by trends and aesthetics? • Colour alterations • Facade alterations	[ ] Strong [ ] Some [ ] Non	
3	Carry over		
	Is this subsystem likely to change from generation to generation and therefore should be a separate module?	[ ] Very possible [ ] Possible [ ] Not Possible	
4	Product planning		
	Are there reasons why this part of the plantroom should be a separate module since it is the carrier of product functional features?	[ ] Strong [ ] Some [ ] Non	
5	Technology evolution		
	How likely is this subsystem to experience advancements in technology?	[ ] Very possible [ ] Possible [ ] Not Possible	
6	Manufacturing process compliance		
	Are there reasons why this part should be a separate module because: • The lead time differs extraordinary? • It has a suitable work content for a group? • Simultaneous manufacturing and assembly?	[ ] Strong [ ] Some [ ] Non	
7	Common unit		
	Is this part of the plantroom the same in all product variations?	[ ] Yes [ ] Mostly [ ] Non	
8	Manufacturing		
	Are there reasons why this part should be a separate module because: • It will be an ergonomic part to handle? • The production machinery can be re-used? • Machinery operations and reachability restrictions? • Size restrictions?	[ ] Strong [ ] Some [ ] Non	
9	Separate testing		
	Are there reasons why this part should be a separate module because it can be tested separately?	[ ] Yes [ ] No	
10	Purchasing		

	Are there reasons why this plantroom subsystem should be a separate module? • This subsystem can be bought at a black box from external suppliers? • The logistics cost can be reduced? • The capacity can be balanced?	[ ] Strong [ ] Some [ ] Non	
11	Maintenance		
	Is there a reason to have this component to be made a separate module due to maintenance issue? • Likelihood of maintenance • Maintainability • Accessibility / reachability • Safely • Tooling	[ ] Strong [ ] Some [ ] No	
12	Product upgrading		
	Is it possible to upgrade the plantroom by changing this subsystem only?	[ ] Yes [ ] Mostly [ ] No	
13	Recycling: reuse and disposal		
	Is it possible to keep the polluting material or exhaust in this part?	[ ] Yes [ ] Mostly [ ] No	
14	Architectural		
	What is the likelihood that there may be architectural or building requirements or restrictions that could be imposed on this component? • Bolting issues • Size restriction • Ventilation • Fuel / Exhausts • Orientation and Accessibility	[ ] Strong [ ] Some [ ] No	
15	Transportability		
	Is there reason that this component may be developed or restricted to support transportability issues? • Transportation aide devices	[ ] Strong [ ] Some [ ] No	

Appendix 3: Requirement trees



Functional Requirements (Level 2: Apartment Building)

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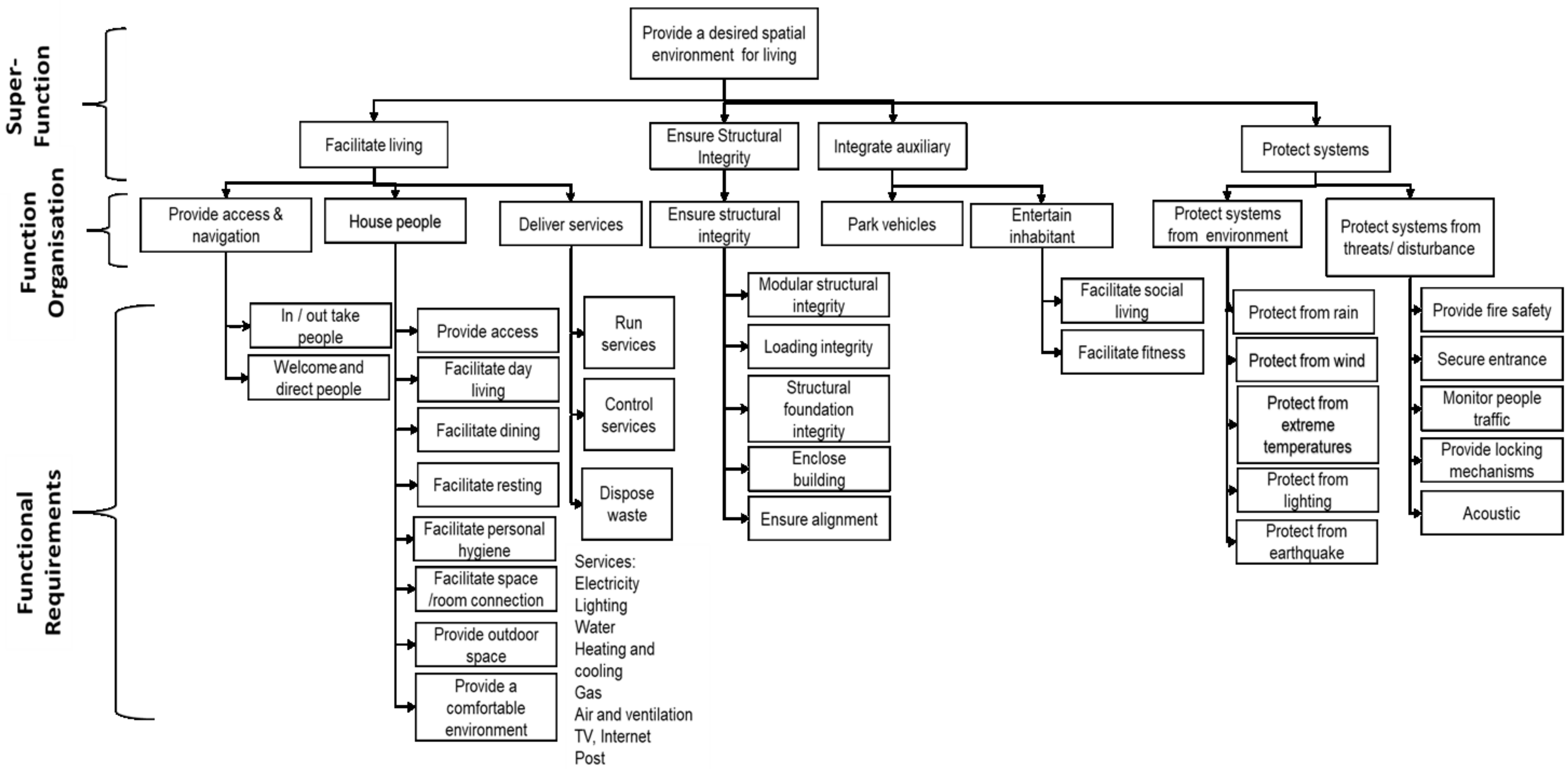

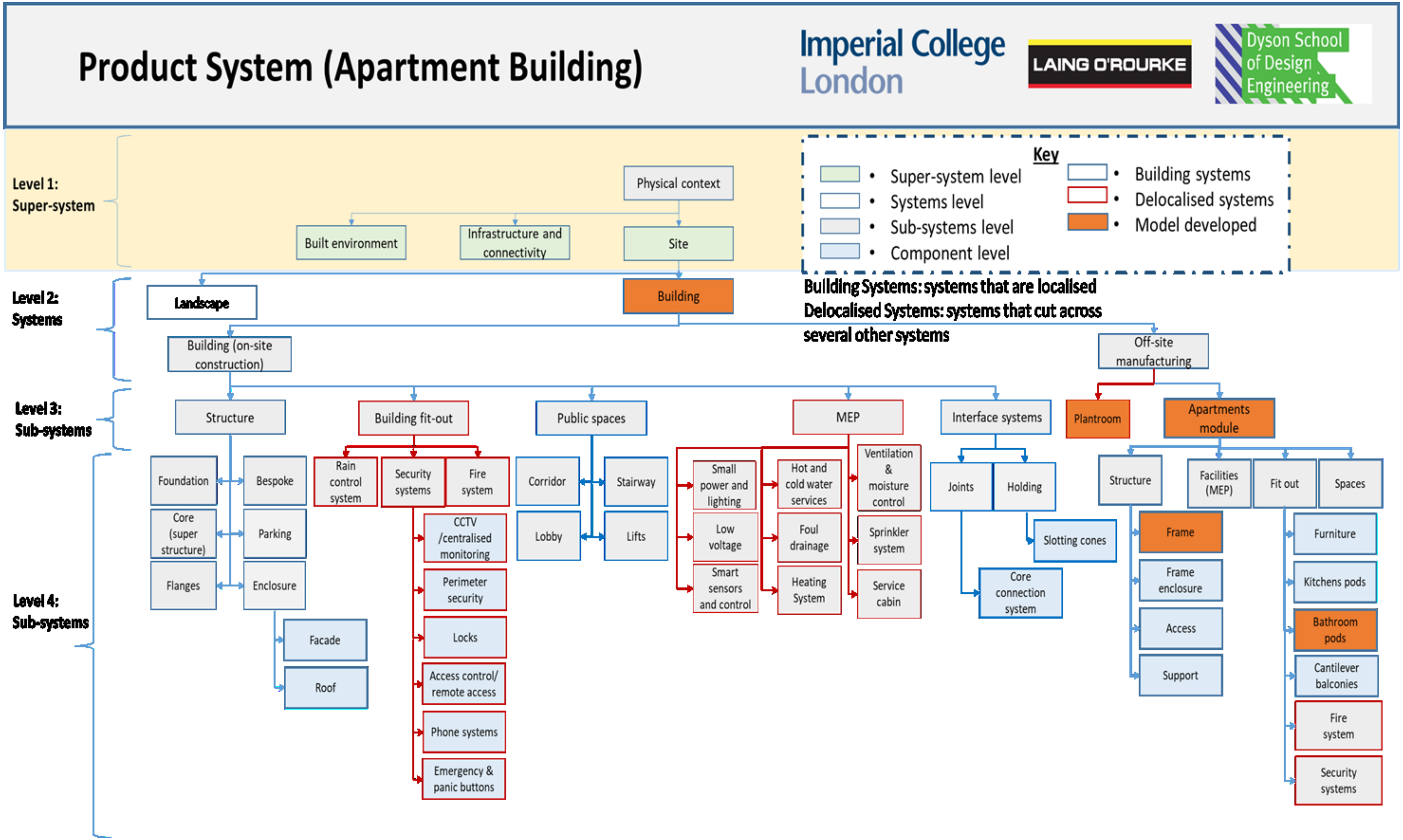

Product System (Apartment Building)
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Level 1: Super-system
Physical context
Built environment
Infrastructure and connectivity
Site
Key
Super-system level
Systems level
Sub-systems level
Component level
Building systems
Delocalised systems
Model developed
Level 2: Systems
Landscape
Building
Building Systems: systems that are localised
Delocalised Systems: systems that cut across several other systems
Building (on-site construction)
Off-site manufacturing
Level 3: Sub-systems
Structure
Building fit-out
Public spaces
MEP
Interface systems
Plantroom
Apartments module
Level 4: Sub-systems
Foundation
Bespoke
Core (super structure)
Parking
Flanges
Enclosure
Facade
Roof
Rain control system
Security systems
Fire system
CCTV /centralised monitoring
Perimeter security
Locks
Access control/ remote access
Phone systems
Emergency & panic buttons
Corridor
Stairway
Lobby
Lifts
Small power and lighting
Low voltage
Smart sensors and control
Hot and cold water services
Foul drainage
Heating System
Ventilation & moisture control
Sprinkler system
Service cabin
Joints
Holding
Slotting cones
Core connection system
Structure
Facilities (MEP)
Fit out
Spaces
Frame
Frame enclosure
Access
Support
Furniture
Kitchens pods
Bathroom pods
Cantilever balconies
Fire system
Security systems

Non-Functional Requirements (Level 3: Apartment Module)

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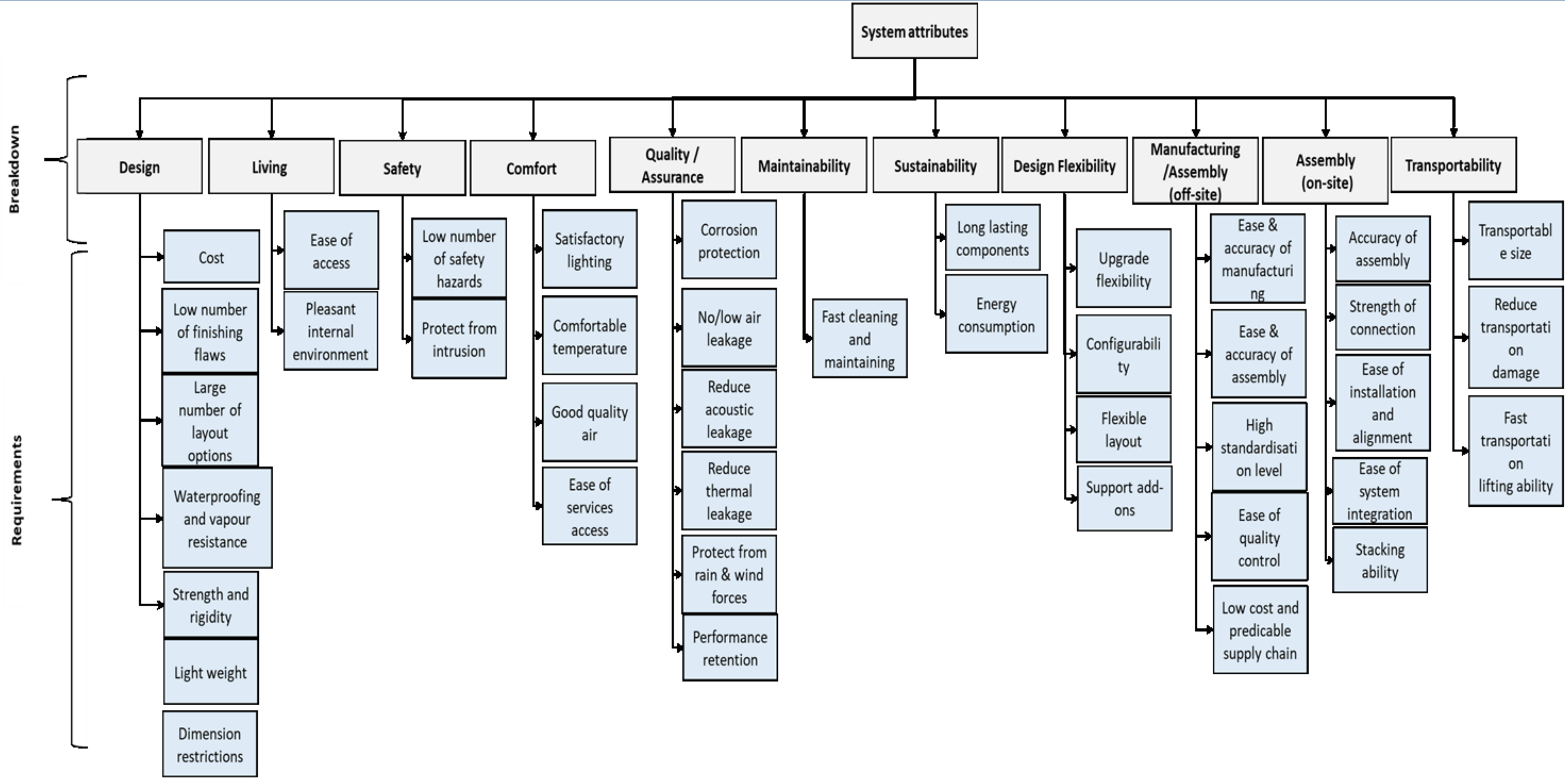
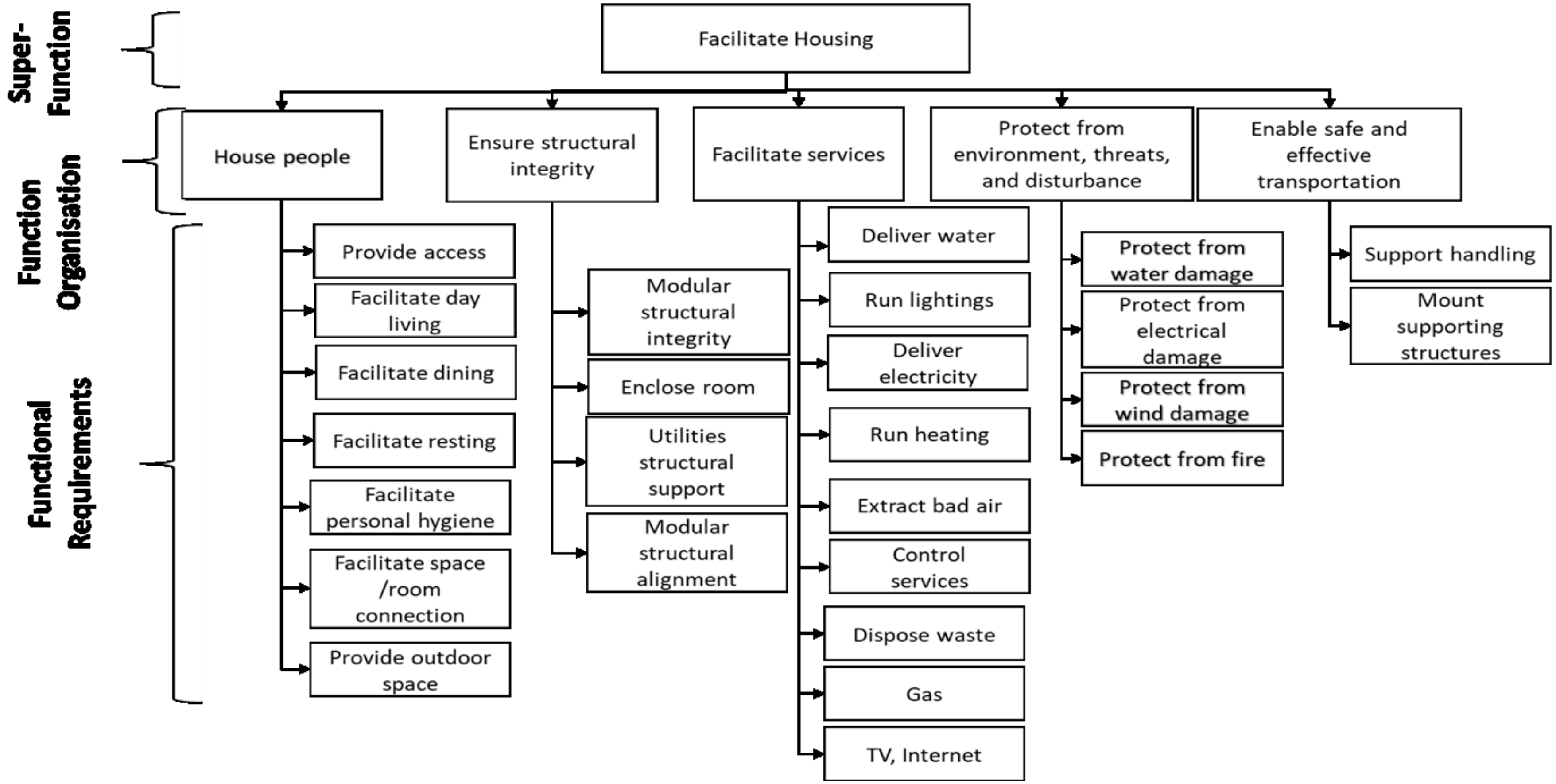
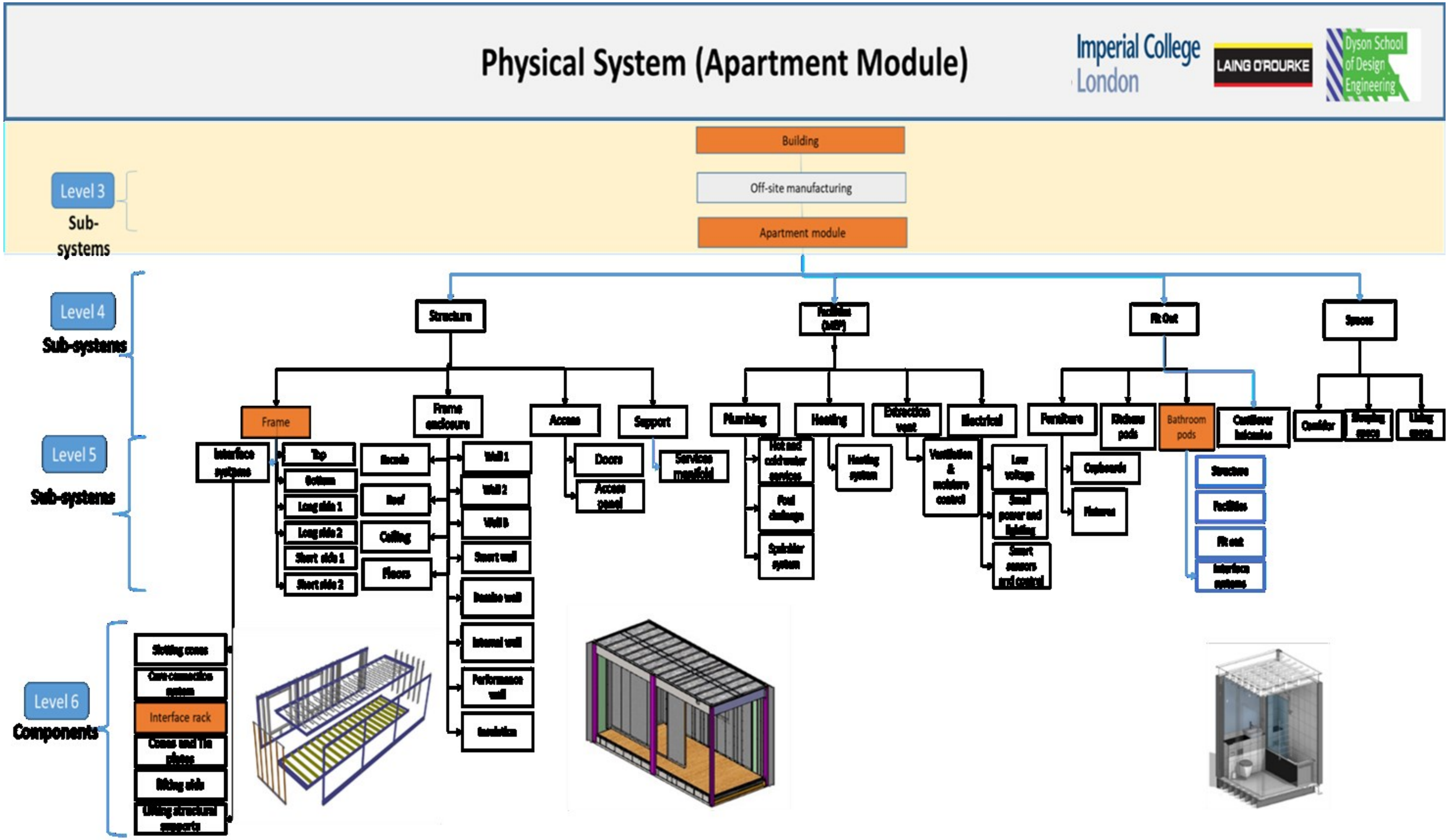


Functional Requirements (Level 3: Apartment Module)





Physical System (Apartment Module)
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Building
Off-site manufacturing
Apartment module
Level 3
Sub-systems
Level 4
Sub-systems
Level 5
Sub-systems
Level 6
Components
Structure
Fit Out
Space
Frame
Frame enclosure
Access
Support
Plumbing
Heating
Extraction vent
Electrical
Furniture
Kitchen pods
Bathroom pods
Cantilever balconies
Corridor
Sleeping space
Living space
Interface systems
Top
Bottom
Long side 1
Long side 2
Short side 1
Short side 2
Facade
Roof
Ceiling
Floors
Wall 1
Wall 2
Wall 3
Smart wall
Internal wall
Performance wall
Insulation
Doors
Access panel
Services manifold
Hot and cold water services
Foul drainage
Sprinkler system
Heating system
Ventilation & moisture control
Low voltage
Small power and lighting
Smart sensors and control
Cupboards
Fixtures
Structure
Facilities
Fit out
Interface systems
Slotting cones
Cone connection system
Interface rack
Cones and Tie plates
Lifting side
Lifting structural supports

Non-Functional Requirements (Level 4: Bathroom Pods)

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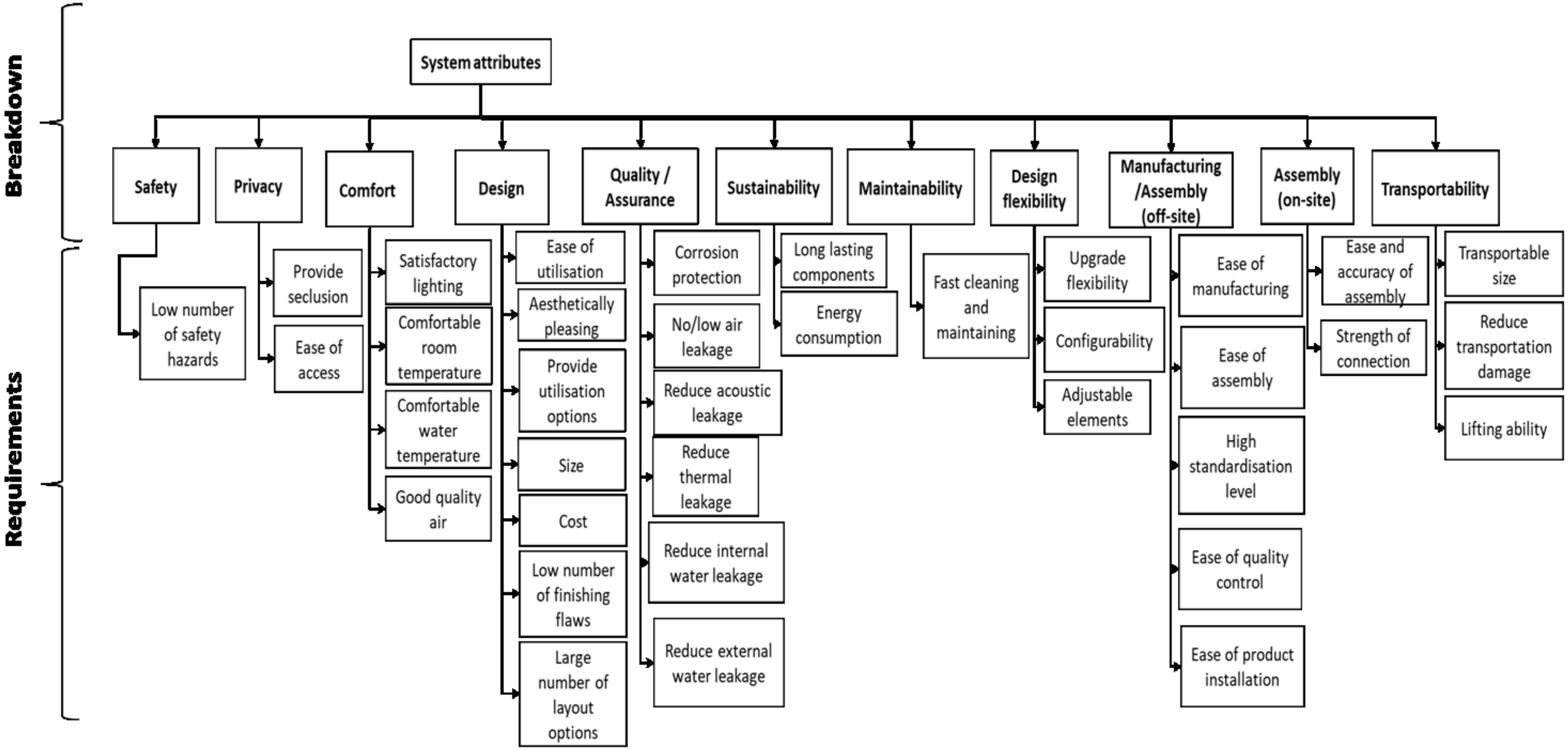

Functional Requirements (Level 4: Bathroom Pods)

Imperial College London

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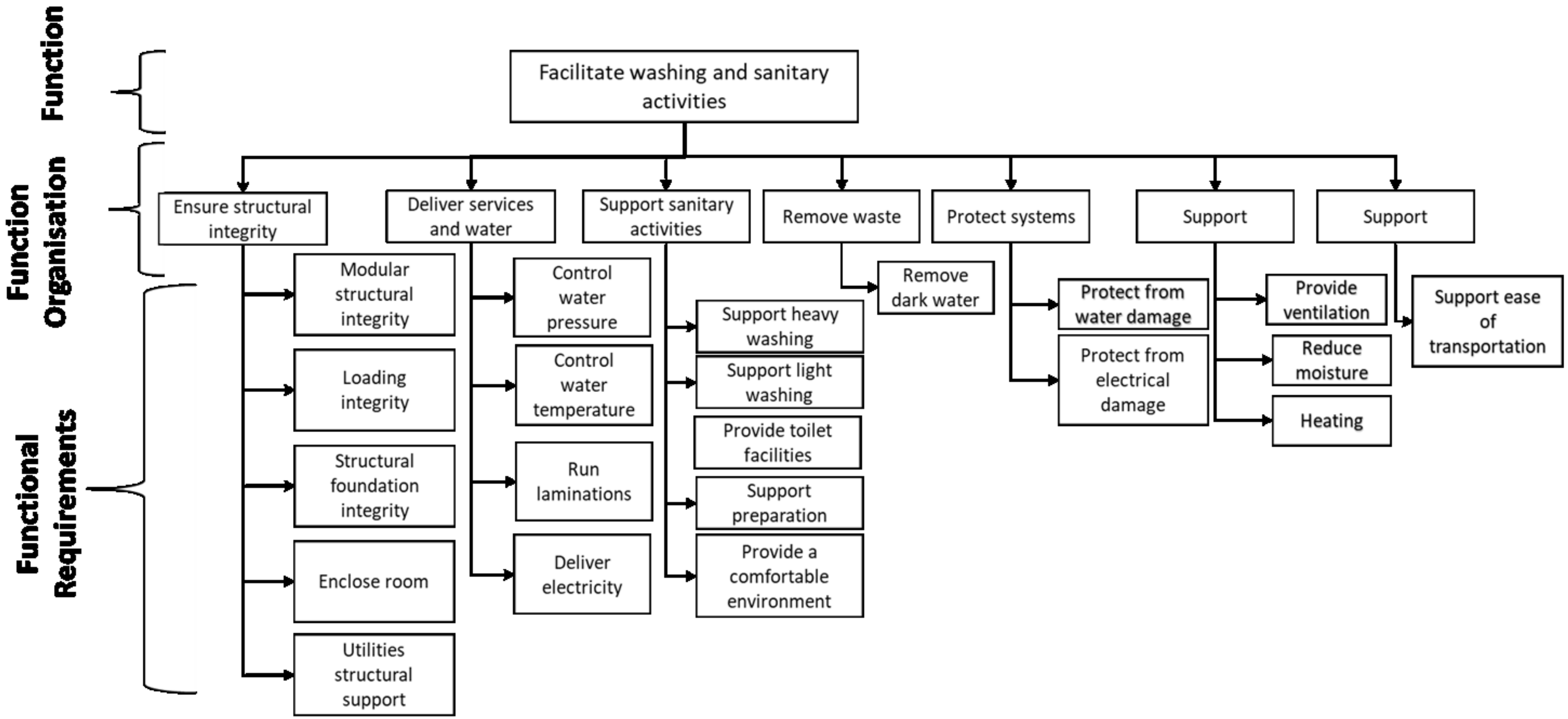

Physical System (Bathroom Pods)

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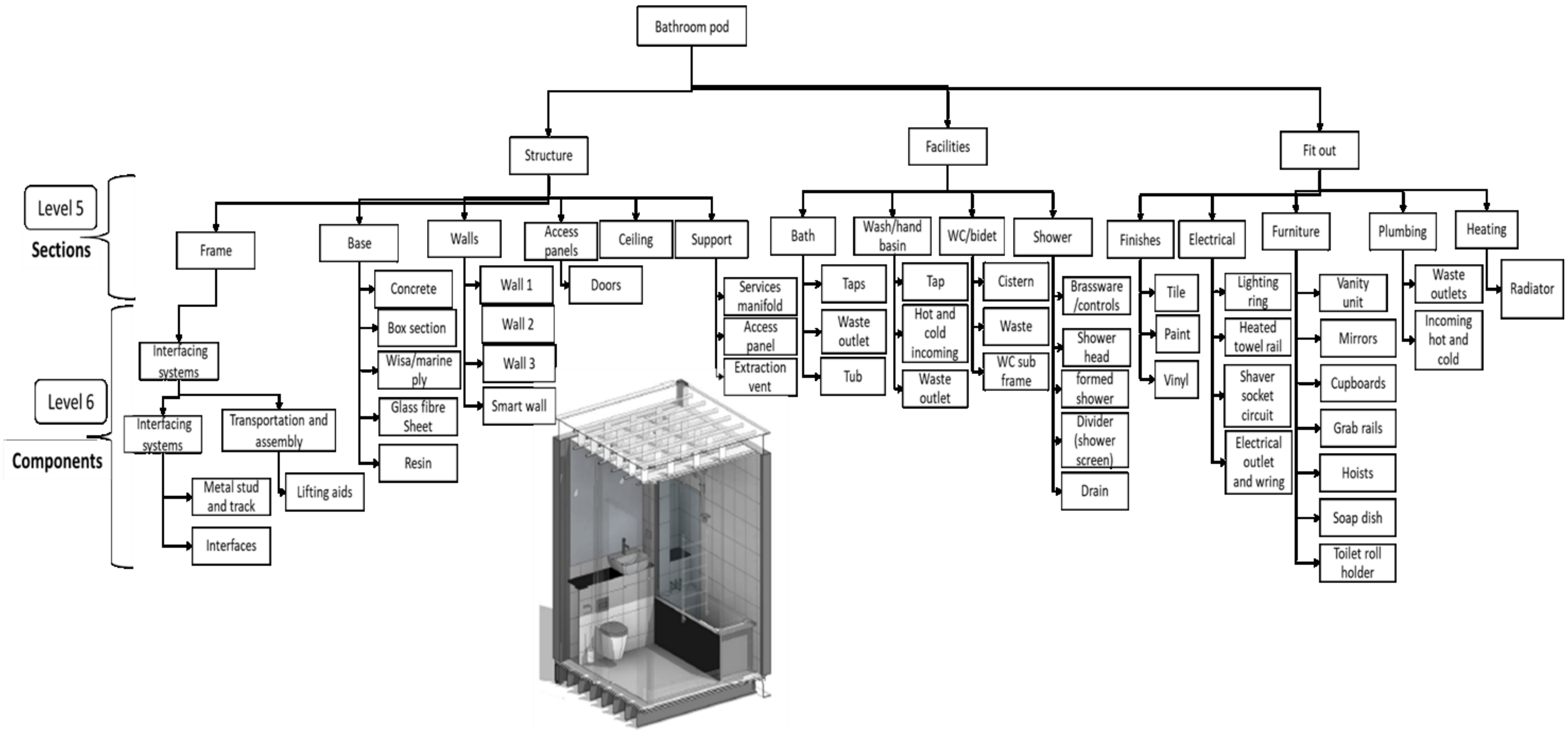

Non-Functional Requirements (Level 5: Frame)

Design	Cost
	Low number of finishing flaws
	Waterproofing and vapour resistance
	Strength and rigidity
	Light weight
	Dimension restrictions
	Pleasant internal environment
Safety	Low number of safety hazards
Comfort	Satisfactory lighting
	Comfortable temperature
Quality / Assurance	Corrosion protection
	No/Low air leakage
	Reduce acoustic leakage
	Reduce thermal leakage
	Protect from rain and wind forces
	Performance retention
Maintainability	Fast cleaning and maintaining
Sustainability	Long lasting components
	Energy consumption
Design flexibility	Upgrade flexibility
	Configurability
	Flexible layout
	Support add-ons
Manufacturing /Assembly (off-site)	Ease and accuracy of manufacturing
	Ease and accuracy of assembly
	High standardisation level
	Ease of quality control
	Low cost and predicable supply chain
Assembly (on-site)	Accuracy of assembly
	Strength of connection
	Ease of installation and alignment
	Ease of system integration
	Stacking ability
Transportability	Transportable size
	Reduce transportation damage
	Fast transportation
	Lifting ability

Functional Requirements (Level 5: Module Frame)

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Ensure structural integrity	Module structural integrity (internal and external loads)
	Support internal mounts
	Support utilities structurally
Ensure structural functionality	Define room envelope
	Retain internal mounts
	Locate internal mounts
	Support geometric flexibility
Interface	Align module
	Allow mounting add-on (balcony and additional space)
Protect systems	Protect from water damage (corrosion or expansion)
	Protect from wind damage (corrosion or expansion)
	Protect from fire damage (corrosion or expansion)
Transport aid	Facilitate transportation

Physical System (Frames)