# Developing an Integrated Design Support Framework to Enable Mass-Customisation in Multi-Storey Timber Building Projects

**by Alireza Jalali Yazdi**

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under the supervision of
Dr. Alireza Ahmadian Fard Fini
Dr. Ali Akbar Nezhad
Dr. Michael Er

University of Technology Sydney
Faculty of Design, Architecture and Building

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Alireza Jalali Yazdi declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Built Environment, Faculty of Design, Architecture and Building at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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# Acknowledgement

*To my parents, for all their support and unconditional love*

This is a thesis by compilation

# Declaration of Publications

The following publications, which have arisen from the research for this thesis, are listed below:

1. **Alireza Jalali Yazdi**, Alireza Ahmadian Fard Fini, and Perry Forsythe. "An Integrated Product Planning and Design Platform in the Context of Housebuilding Industry." Construction Research Congress 2020: Computer Applications. Reston, VA: American Society of Civil Engineers, 2020.

2. **Alireza Jalali Yazdi**, Alireza Ahmadian Fard Fini, and Perry Forsythe. "Mass-customisation of cross-laminated timber wall systems at early design stages." Automation in Construction 132 (2021): 103938.

3. **Alireza Jalali Yazdi**, Alireza Ahmadian Fard Fini, Ali AkbarNezhad, Michael Er. "DfMA-oriented Optimization of Cross-Laminated Timber wall systems in multi-storey buildings"

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Signature of Author | Date:
Alireza Jalali Yazdi | Production Note: Signature removed prior to publication. | 28/03/2023

Signature of Co-Author | Date:
Perry FORSYTHE | Production Note: Signature removed prior to publication. | 6/4/2023

Signature of Co-Author | Date:
Michael Er | Production Note: Signature removed prior to publication. | 6/4/2023

Signature of Co-Author | Date:
Ali Akbar Nezhad | Production Note: Signature removed prior to publication. | 6/4/2023

Signature of Co-Author | Date: 21/4/2023
Alireza Ahmadian Fard Fini | Production Note: Signature removed prior to publication.

# Abstract

The building industry has adopted mass-customisation (MC) strategies to address efficiency issues associated with the customised nature of this sector. Multi-storey apartment buildings constitute a large segment of the Australian building sector, which possesses significant potential for MC. MC aims to provide choices for heterogeneous apartment demands in a prefabricated construction context. It intends to deliver marketable building products at a competitive cost close to mass-produced buildings. To maximise their benefits, mass-customisation strategies must be implemented from early design stages by developing a custom product that can be efficiently manufactured, transported and assembled onsite. Implementation of general design rules, such as guidelines provided by Design for Manufacture and Assemble (DfMA), at the early design stages can enable the mass-customisability of the final building product. Implementing such generic DfMA rules is challenging, particularly due to the mathematical complexity of the building design problem. To successfully address this challenge, a systematic and automatic approach is necessary for exploring different design alternatives. However, the literature is slim in proposing a practical solution to optimise the design for MC. Such an optimisation platform must incorporate offsite manufacturing processes and efficient onsite assembly and installation operations into the design process.

This research introduces a design support framework that enables MC of multi-storey buildings by incorporating both offsite manufacturing and onsite assembly requirements. The framework consists of three main components: (1) a design optimisation model to maximise standardisation while maintaining architectural flexibility, (2) a framework for transferring the optimisation results to a digital design platform, and (3) an onsite installation optimisation model for crane scheduling to avoid the formation of bottlenecks in assembling mass-customised components. Due to their increasing market uptake, and their high potential for customisation, Cross-Laminated Timber (CLT) buildings are chosen as the case studies for the implementation of MC strategies. The mass-customised building designs were automatically generated and thoroughly explored using evolutionary algorithms. The optimal design solutions were visualised on a Building Information Modelling platform and then were used to generate an accurate bill of quantities for factory production. Results of the case studies showed that up to a 20% decrease in the CLT waste and a 10% decrease in the installation, delays are achievable by adopting the proposed methodologies. The outcomes of this research can be used by the building industry to achieve mass-customised designs that result in minimal waste during manufacture and a more productive onsite installation.

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# Chapter 1

## Introduction

## 1.1 Productivity issues and mass-customisation

Historically, residential construction has been a craft-based industry, delivering the building as a product with an Engineer-To-Order (ETO) strategy [1]. In this strategy, the building is engineered in response to the customer's order, leading to labour-intensive on-site production processes [2, 3]. This view towards residential construction changed significantly after the Second World War in response to the housing shortage and the need to cater for the growing housing demand [4]. Accordingly, in the first half of the twentieth century, the housing industry began assimilating into manufacturing industries [5], which had adopted and benefited from industrial production concepts such as lean and agile manufacturing. This transition had been conceptually inspired largely by Henry Ford's assembly line of cars [6, 7], and has proven to result in lower unit costs and shorter construction time.

Despite the possibility of lower costs for construction, the inability to meet the custom design preferences of purchasers has resulted in a negative perception of off-site, mass-manufacturing construction methods which continue to date [8]. Achieving a balance between the level of standardisation and customisation in the design of mass-manufacturing construction strategies is, therefore, crucial [9, 10].

To address the above challenge, the concept of MC has emerged as a strategy to maintain a balance between two opposing production concepts: customisation and Mass-Production (MP). It is a systematic notion that employs various technologies, organisational structures, and agile, flexible and integrated processes to provide products and services specifically designed for each customer at a cost close to that of MP [11, 12]. The concept of product MC covers a wide scope, including marketing, planning, design, manufacturing, assembly and supply of the product [13]. Successful implementation of MC concept in practice requires a high level of industrial production to promote mass-producibility and efficient production in a relatively customised context [14, 15].

The adoption of industrial production concepts from the manufacturing industry was realised in two forms: i) moving a majority of the site operations to a controlled and optimised factory environment, and ii) adopting manufacturing automation technologies as a replacement for less efficient onsite processes to increase construction productivity and minimise waste. The effects of offsite fabrication on the construction industry's productivity can be adverse since it enables fundamental changes in the production strategy and adopting a strategy closer to Make-To-Stock (MTS). As a result of this shift, the individual customer's requirements may be overlooked in the design stage to gain greater production efficiency. The resulting decreased customisation to meet customers' needs can negatively affect the serviceable obtainable market of the industrialised construction companies. The MC strategy is deemed to provide a solution to meet the market's demand for customised dwellings within a productive industrial housing manufacturing strategy by creating a balance between standardisation and customisation [7, 16]. MC combines the controversial goals of individualisation and cost-efficient production [17]. It aims to provide customised products or services through flexible processes in high volumes and reasonably low costs, i.e., close to that of MP [18, 19].

MC strategies can be implemented in different areas, including marketing, planning, design, manufacturing, assembly and supply of the product[20]. The ultimate goal is to keep the processes as standard as possible throughout the entire value chain while the physical product becomes more specific along the chain towards a custom product for the end-user. When standardising Supply-Chain (SC) processes, the design phase is of extreme importance since it is the bottleneck for streamlining the entire manufacturing process [21]. A good design maximises the commonality or standardisation in building components while maintaining architectural flexibility to create custom building products with higher market values [22, 23]. A prerequisite for attaining the goals of MC is to utilise the modularisation strategy widely used by manufacturing. It fosters reusing a limited set of components across a range of different products [14].

Modularisation attempts to create new products by mixing and matching a set of sub-products or components, creating a set of various products out of mass-produced modules. The level of product breakdown is an essential consideration when defining a modular structure for the building as the final product [24]. Different levels of breakdown have been employed for building construction, ranging from breaking a building down into standard components to complete modularisation of the entire dwelling in the form of large volumetric units [25]. When defining the modular breakdown structure, large sub-products can negatively impact the customisation element of the final product, while breaking down the product further into smaller sub-products will cause production inefficiency [26, 27]. In line with this, an optimal modularisation outcome may be achieved by avoiding the breakdown of building components into smaller components unless customers specifically request tailored solutions relevant to that component. This allows maximising the level of standardisation while at the same time enabling customisation when required.

Living spaces are the most basic and important of the functions that the building provides to the end user. Limiting the enclosed spaces to a few options and using the prefabricated volumetric modules might be extremely cheap but will eventually cause a loss of revenue due to the low perceived quality [28, 29]. A better option is to break down these modules into their sub-components, creating an enormous opportunity for potential variety among different products. Therefore, non-volumetric preassembly systems can be a far better option when addressing various preferences of the contemporary market. In these systems, the largest predefined sub-product is defined such that it does not enclose living spaces, making them easier to manufacture, handle and transport, but adds to the complexity of their onsite assembly.

A good example of non-volumetric preassembly systems is the CLT panelised system, which uses timber wall and floor panels as the structural components, and connects them to form enclosed spaces. CLT reduces construction time, produces less waste and results in lighter buildings with higher comfort and building performance [30, 31]. It is a highly machinable material that enables the off-site production of building panels with various sizes suitable for different building layouts [32]. Besides its productivity benefits, as a result of timber's lower embodied carbon compared to other construction materials, when considering trees' carbon sequestration, CLT construction is recognised to have the potential to revolutionise the construction industry into a giant carbon sink [33].

Decisions regarding the building design are made at different stages, including conceptual, preliminary, and detailed design. A successful MC design, however, relies on early planning of the product for manufacture and build processes to meet customer requirements [32]. Thus, the implementation of the open-building notion should start early. Moreover, the literature suggests that

80% of the construction resources will be allocated based on the decisions made in the early design stages [34]. Early decisions regarding the structural system, spatial forms and the optimum location of structural members (topology optimisation) can greatly influence the build processes of the final building. Because design-related problems are inherently complex [35, 36], introducing the complexity of such processes [37] exacerbates this condition. A remedy to this complexity is the automation of design.

As one of the core capabilities of MC, flexible automation [38] uses automated processes across all production phases [39] to handle this complexity. Automating the design process decreases not only the lead time caused by errors or variations through efficient search in the design space but also assists rapid and flexible estimating prior to tender through early supplier involvement [40, 41]. Nonetheless, the literature on automating the design process tend to overlook the effect of design decisions on the production and build phases which is a major drawback, especially in modular construction, where design decision can significantly affect production and assembly efficiency. In particular, MC has not been addressed when automating the process of building design. Rather, the extant literature predominantly focuses on bringing design attributes of one discipline, for instance, architectural and structural attributes, into the automation process [42, 43]. There are a limited number of studies that have taken interdisciplinary Design Parameters (DPs) into account of design automation [37, 44]. Such studies, however, have no allowance for production and construction processes.

Similarly, successful MC implementation requires a streamlined on-site operations plan to ensure manufacturing and operations requirements are taken into consideration in overall process optimisation. Although a high amount of production operations is moved to the more controlled and efficient environment of factories, there are still inevitable installation works onsite [45, 46]. These operations involve storage, handling, lifting, and assembly of the prefabricated elements. Thus, despite highly efficient offsite production processes, the overall efficiency of such projects can be hindered by unproductive onsite processes. This inefficiency exacerbates in CLT systems, where overall economic viability is highly dependent on efficient onsite installation processes [47, 48]. Therefore, successful implementation of MC strategies requires efficient onsite operations to ensure the efficiency gained from factory production is not offset by potential on-site inefficiencies.

The present work aims at addressing the challenges highlighted above by developing a comprehensive framework for automated design and planning of modular CLT construction, to achieve a balance between standardisation and customisation. This goal is accomplished by introducing manufacturing and assembly variables into algorithmic planning and design processes. In doing so, the key knowledge gaps in the literature, as highlighted in detail in the following section, should be addressed.

## 1.2 Research gap

The majority of literature on MC follows two main approaches towards building design, these being customisation-oriented or production-oriented approaches. Customisation-oriented approaches adopted by Bianconi et al. [49], and, Duarte and Correia [50] are commonly inclined towards market satisfaction. These studies make efforts to translate customer requirements into DPs, and generate several feasible options for the customer to choose from. These methods are strong in terms of algorithmic design and optimisation but mainly address architectural objectives. The results of these methods are overly individualised and lack a view toward production in the MC balance.

Production-oriented methods, on the other hand, are mainly concerned with improving SC processes. They attempt to introduce knowledge-sharing practices and standards for technical design details or perform optimisation for structural performance objectives. These studies are rich in terms of technical details and physical modelling of structural elements however lack customisation to meet a client's taste.

In summary, there is a weak link between design work and SC processes including manufacturing and onsite assembly. More specifically, the gap in the literature can be defined as the absence of a planning and design framework that promotes the following capabilities:

- Automated generation of designs
- Technical details to improve production operation
- Design flexibility in the architectural parameters
- Optimal onsite installation

Developing such a framework requires responding to the questions enumerated in the next section, to define research objectives and a feasible scope for the research steps.

## 1.3 Research questions

The research questions that drive this research are introduced in this section. Since this research seeks to address two different domains i.e., design and onsite assembly, two main questions are defined. Each of these questions has its own sub-questions, leading to better-defined details in terms of technical objectives and scope.

1. How to mass-customise the design for optimal manufacturing?

    - At what stage should our model enter the decision-making process?
    - Which components should be focused on?
    - Which building features should be standardised or customised?
    - How to achieve a balance between standardisation and customisation in the design?
    - How to share design knowledge, when the optimal design is achieved?

2. How to optimise the onsite operations to make sure that our MC designs are installed optimally?

    - Which onsite operations are the most critical?
    - Which characteristics of the prefabricated system negatively affect these operations?
    - How to alleviate these effects?

### 1.3.1 Question 1

To mass-customise the designs for optimal manufacturing, the point of entry in the design work is extremely important. The design work involves different stages, each making effort to define a part of the final building. Since MC strategies focus on two factors, i.e., MP and customisation, each stage focusing on certain stages can limit the design freedom to address either architectural customisation or components manufacturing. The component type itself must be chosen carefully since some components can either limit one side of the MC balance or not be effective on either. Therefore, a balancing strategy must be planned so that one factor is carefully controlled and the other is improved (e.g., maintaining the level of customisation while improving manufacturability). It is difficult to plan a strategy that positively affects both ends of the balance, due to their counteracting nature. In the end, the resulting designs and their technical details need a practical strategy to be communicated and applicable.

### 1.3.2 Question 2

Efficient on-site assembly is a critical operational factor in ensuring the optimisation of benefits associated with factory and mass-customised designs. The critical operations causing the most inefficiency, and the characteristics of the project that interact with these operations must be identified. This identification helps tackle the issue from both the design work and planning of the operation itself. Therefore, a detailed plan for managing these inefficiencies must be developed.

## 1.4 Research objectives

The central objective of this research is to develop an automated framework to integrate SC processes into the design and planning stages, as a step towards adopting MC strategies. To this end, and to respond to the research questions defined in the previous section, this research pursues the following objectives:

1. Achieving mass-customisability through a design system
    - Choosing the best design stage to optimise
    - Choosing the best component type for standardisation
    - Choosing architectural characteristics for customisation

- Finding design variables that satisfy both standardisation and customisation
- Develop a design knowledge-sharing strategy

2. Achieving onsite efficiency for a mass-customised building

- Finding onsite operations causing the most inefficiency
- Identifying characteristics of building systems affecting these operations
- Developing optimisation strategies for inefficient operations

## 1.5 Research scope

The scope of this research has been defined so as to achieve each of the aforementioned objectives. This chapter goes through the research scope from different perspectives including the market, building system, and objectives and variables pertaining to design, manufacturing and assembly processes. Fig. 1.1 shows a summary of the scope defined for this research.

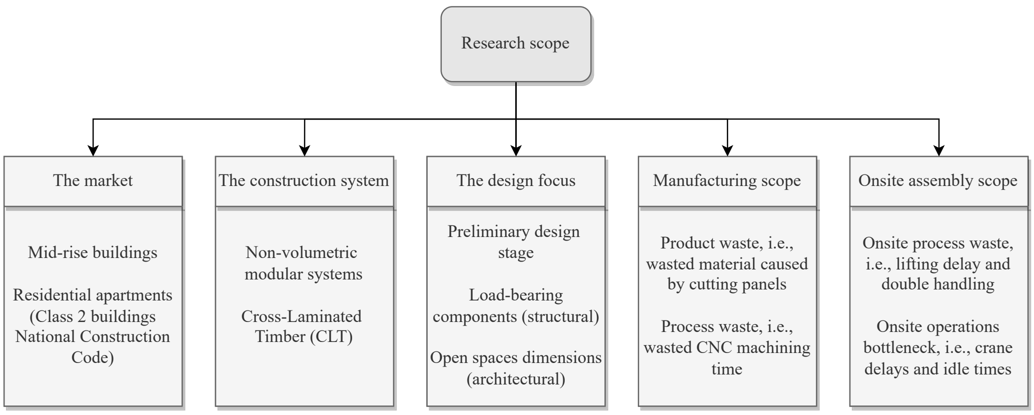



Figure 1.1: A summary of the research scope

### 1.5.1 The market

Construction of new dwellings, including houses and apartments, is a major contributor to the overall Australian economy [51]. Fig. 1.2 extracted from the Australian Bureau of Statistics website, shows the nationwide value of building types by building type. The trend indicates that despite fluctuations in the total value, a larger part of the building industry's economy has been assigned to residential dwellings, over a 15-year span. Thus, this thesis focuses on residential dwellings, specifically mid- to high-rise buildings.

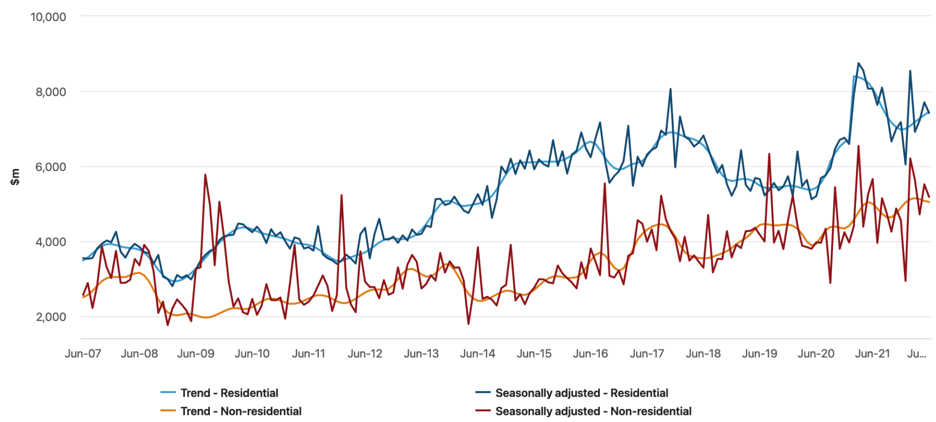



Figure 1.2: Value of building approved, by building type

Residential buildings are classified into three classes in the NCC as shown in Fig. 1.3. Among these classes, classes 1 and 2 can potentially be included in the scope of this research, since they are residential and can be bought and sold by the end-users. However, the scope is limited to class 2 for the higher MC potential they offer.

Single houses are usually designed individually and are used by a single family. They are usually designed to order, with the exception of mass-builder companies that build a large number of houses based on their pre-designed catalogue of houses. Since these buildings do not need complex structural

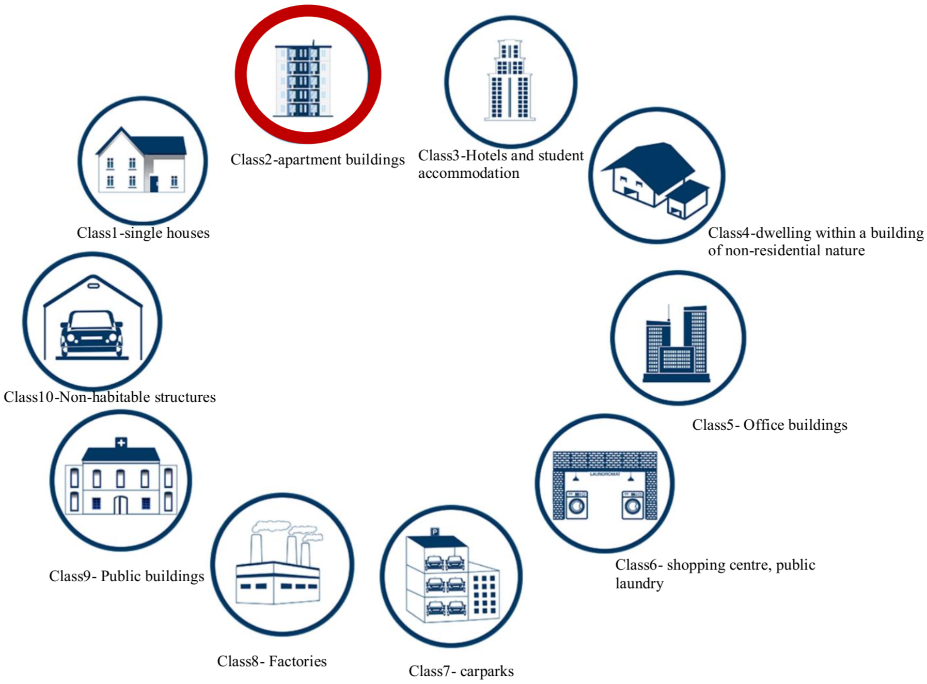



Figure 1.3: Building classifications under the NCC

systems and large volumes of materials, they offer a low potential for MC of parts. Further, customisation is a non-negotiable in these buildings since the buyer is paying higher prices, and providing customisation does not require design effort in simple structural systems.

Class 2 apartment buildings, on the other hand, comprise a number of separate dwellings, with a significantly larger volume of materials and components. The end-users of apartment dwellings commonly do not contribute to the layout design of their units, which provides the builder with a great opportunity to manipulate the design for other objectives (i.e., SC processes).

In contrast to houses, mid-rise and high-rise buildings usually include multiple dwellings on the same floor. These dwellings affect each other in terms of space, noise, and building systems (e.g., Electrical, HVAC, safety, lighting, energy, etc.). Thus, from the architectural point of view, the layout design for each floor is a 2D combinatorial optimisation with several variables and performance criteria. A model that is able to handle the design complexity of mid-rise projects can also be utilised among a set of house projects with more flexibility in variables since there is no spatial relation among separate dwellings. From the production's point of view, these buildings contain significantly higher amounts of materials and a larger number of components in the case of prefabricated buildings. This would mean a lot more working hours, machinery and overhead costs, which add up to the total costs of the project. The larger number of structural and non-structural elements will also enable design work to implement standardisation of building sub-products even at the project level, due to a large number of components. In contrast, house projects do not provide such flexibility.

In the case of houses, the structure usually supports a single dwelling, and every alteration in inner structural elements affects the separation of living spaces in the dwelling. In apartment buildings, however, the layout design and the structural design together can be manipulated in a way that the structural elements are placed in spaces among separate dwellings. Thus, the number of unfavourable impacts of structural design changes on the apartments' living spaces can be minimised.

### 1.5.2 The construction system

In an industrial construction context, prefabricated systems are promoted as a means to achieve operational efficiency through standard processes. To maintain an acceptable level of customisation, it is necessary to avoid predefining architectural characteristics that are in direct interaction with the end user. Therefore, volumetric systems that use standard living spaces as the forming module of the final dwelling, are not suggested. In comparison, non-volumetric/planar systems can provide higher architectural flexibility.

CLT is a non-volumetric green structural system with an increasing market uptake in recent years. Panelised CLT systems are constructed using planar timber components utilised as load-bearing elements including walls and floors. CLT system is therefore chosen as the implementation case for this thesis. Structural specifications of the CLT systems are also suitable for mid- to high-rise buildings, making them a proper choice for multi-storey residential buildings as the focus of this research.

### 1.5.3 The design focus

In this research, the structural components are focused on due to their large share in total project cost, as well as material usage. In a panelised CLT building system, the main structural elements are wall and floor panels. Decisions regarding the placement and the geometry of wall panels can affect the architectural layout since these elements will enclose and separate living spaces. Therefore, for the design optimisation part of the research, the geometry of wall components will be the main variable. The floor panels will be used for the implementation of the onsite assembly optimisation, as will be discussed later on.

For the purpose of this research, the preliminary design stage has been chosen for implementing the design optimisation system. The design work starts with this stage, where the structural system is chosen, and general architectural specifications, such as floor plates and initial placement and geometries of the structural elements are determined. At this stage, a detailed architectural layout is yet to be defined, making it a very suitable timing for implementing MC on the large and heavy structural elements. The reason is that the main objective of the customisation involves the design of living spaces in the architectural layout, and the design work has greater freedom in deciding the geometries of structural elements.

### 1.5.4 Manufacturing scope

The design support tool efforts to find the best structural wall geometries to maximise the design performance for manufacturing and assembly processes. To do so, the design will try to design structural members so that they produce minimum cut waste in the CLT manufacturing facility. Material waste is of strong significance in this structural system, since CLT is a rather expensive material, and conventional custom designs usually lead to large amounts of waste. This waste is transferred to the builder in the form of higher material costs, making the final building more expensive for the customer.

The other objective of the design support tool is to minimise variety among all structural member geometries. This commonality in the manufactured components leads to decreases in the delays in panel cutting time using CNC machine. similar panels require less frequent changes to be made in the machine setup, and therefore reduce the total machine setup times. Further, common component geometries can lead to a better learning curve for the assembly team as well, causing faster assembly operations as the project progresses.

### 1.5.5 Onsite assembly scope

The final part of the research will focus on optimising the onsite assembly operations to ensure overall productivity gain due to the MC system presented. CLT projects involve the installation of numerous heavy structural components, which can only be lifted to their assembly location using lifting machinery. Therefore, these machines become the bottleneck for the onsite assembly processes, and their delays and idle times will directly delay the project completion. Therefore, the optimisation algorithm focuses on minimising crane delays caused by wasteful hook motions and double handlings, to deal with this bottleneck.

## 1.6 Thesis organisation

The thesis is organised into seven chapters. Chapters 2 and 7 open and conclude the arguments of the research, and bind the rest of the chapters together. Chapter 2 presents the theoretical foundation of the research, and chapters 3 to 6 form the main body of the dissertation. The correspondence of the thesis chapters with research objectives has been shown in Fig. 1.4.

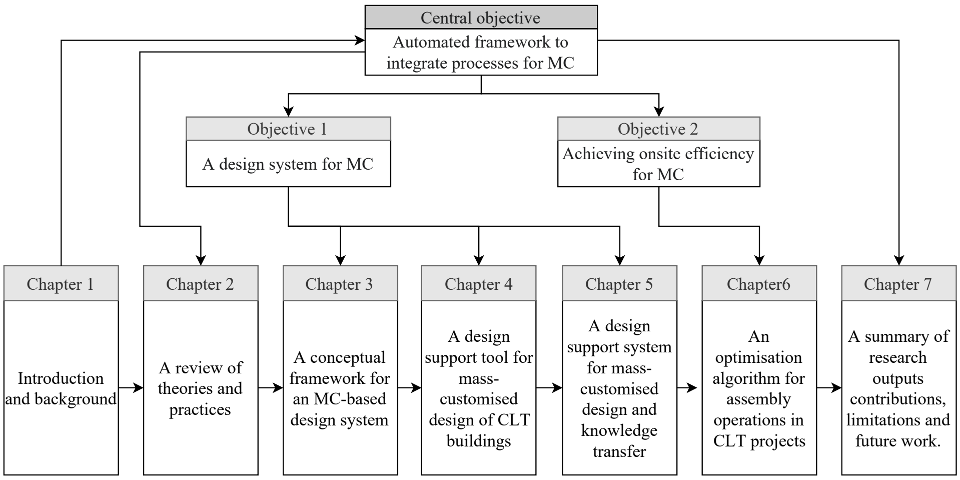



Figure 1.4: Thesis organisation and its connection to research objectives

To improve the logical flow and readability of the thesis, each of the main chapters (3 to 6) include an introductory part, a literature review and outputs and conclusions. While the topics presented in each of these chapters come together in a cohesive framework, each chapter involves a relatively independent area of knowledge requiring investigation.

### 1.6.1 Chapter 1: Introduction

Chapter 1 introduces the background of MC strategies in the construction industry's context. The chapter then discusses the gap in the body of knowledge, and the research design (i.e., questions, objectives and scope) utilised by this research to address this gap.

### 1.6.2 Chapter 2: Theories and concepts

Chapter 2 provides the fundamental arguments supporting this research. The discourse initiates with dissecting the problem (productivity) and the solution (MC), from different perspectives, and establishing connections among them. Further, the chapter discusses the implications of MC strategies on the SCs, in the construction industry. The objective of this chapter is to affirm the propriety of the MC as the response strategy to deal with the productivity issue in construction.

### 1.6.3 Chapter 3: A conceptual framework for applying MC in building design

Chapter 3 presents a framework for a design support tool, that gathers information from SC participants and incorporates them into a design platform. The framework considers the costs and benefits of different design decisions for the SC participants and suggests that the total cost should be minimised as the objective of an automated design system. Operational data from production operations including manufacturing, transportation and assembly, along with design rules and objectives collected from the end-user and the designer, are entered to the optimisation platform. By transforming this set of information into design constraints and objectives, the platform generates a catalogue of optimal designs, to provide choices to the customer in a cost-efficient manner. Further, the framework utilises a combination of product and project approaches toward the housing product, to enable standardisation through modularity, while maintaining the custom nature of the project-based house designs.

### 1.6.4 Chapter 4: Developing a design support tool for mass-cusomising the CLT buildings

This chapter introduces a mathematical optimisation model for the preliminary design of the CLT structures. The model addresses the geometrical specifications of CLT wall panels, as an expensive, heavy and bulky part of the structure. The objectives of this model are set out to conform with the goals of MC, promoting standardisation of the components, while maintaining a level of architectural customisation, acceptable to the end-user. It searches different design alternatives to find wall designs with minimum variety in wall component geometries while following geometry rules dictated by the architect. In addition, the model considers material waste produced by cutting timber panels in CLT manufacturing facilities, due to the high cost of these materials. The model, therefore, finds the optimal balance between material waste and process waste through component standardisation, while conforming to the architectural design rules, as a proxy for customisation.

### 1.6.5 Chapter 5: A practical framework for automated design of CLT buildings for mass-customisability in a digital environment

This Chapter develops a design support framework, for MC of CLT in an integrated BIM environment. The framework consists of three parts: (1) a design optimisation algorithm, (2) a data transfer protocol for taking the optimisation results to the BIM platform, and (3) a workflow for visualisation and cost estimation based on the results of the optimisation in a BIM platform. The optimisation model utilises the rules of the concept of DfMA as the optimisation objectives. Accordingly, a Python program is developed that uses a hybrid optimisation algorithm for finding the best design configuration of the CLT structural wall system. The program uses classes and methods to store the optimisation results and transfer them to the Autodesk Revit application using the Dynamo interface. The resulting Revit model generates a visual model of the structural system and a bill of materials to provide an early cost estimate of the structural members.

### 1.6.6 Chapter 6: An algorithm for efficient onsite installation of mass-customised systems

This chapter develops a mathematical model for optimising crane operations, as a bottleneck for smooth material flow in CLT projects. The research is an attempt to further minimise the inefficiency in the prefabricated construction context, by addressing the inevitable onsite assembly operations associated with these projects. The optimisation model considers CLT-specific assembly requirements and conditions, including (1) stacking and double handling of timber panels, (2) standard nature of the panelisation in CLT projects, causing interchangeability of specific panels for installation, (3) dynamic supply points as a result of double handling on the staging areas, and (4) special considerations that arise due to specific assembly constraints associated with this system. The model also incorporates precise lifting time estimation algorithms from the literature to obtain realistic delay estimates for alternative schedules. The case study uses a renowned industry project as a benchmark for comparison, showing the high performance of the algorithm in generating optimal crane schedules.

### 1.6.7 Chapter 7: Conclusions

This chapter summarises the research and provides conclusions about different parts of the research, binding the main body of the research (chapters 3 to 6) together. Further, the chapter discusses the outputs, contributions, limitations and potential areas for future research.

# Chapter 2

## Theories and Concepts

This chapter reviews the basic concepts and theories pertaining to the MC strategies. The discussion begins with a theoretical discourse about economics and operations management and their relationship with the essence of the MC strategy. The objective of this discussion is to examine the suitability of MC as a response to the productivity issue in the construction industry. Further, the discussion will utilise these concepts to emphasise the validity of this research's approach towards design optimisation. It explains how this approach is utilised to reach the research objectives which are essentially based on the minimisation of product and process "waste". This aims to provide context for the implementation of the proposed optimisation approach in MC context that is discussed thoroughly in chapter 4 and chapter 5.

## 2.1 Theoretical framework

The construction industry accounts for 13% of the world's Gross Domestic Product (GDP) [52]. McKinsey Global Institute [52] states that the industry's productivity growth had been only 1% annually over the past 20 years. This growth rate is low compared to 2.8% for the total world economy and 3.6% for manufacturing. They further state that a 1.6$ trillion value can be added to the world economy by eliminating this productivity gap, meeting half of its infrastructure needs.

According to the Australian Bureau of Statistics, the Australian construction industry accounted for 7.7% of the nation's economy in 2011, grossing $102 billion with over one million people employed. The industry's EBITDA[1] has experienced growths by 10% and 3.3% in the past two years, while the productivity has declined for five consecutive years, falling 4% in 2018-

[1] Earnings Before Interest, Taxes, Depreciation, and Amortisation

2019 financial year. Thus, the annual loss of revenue for the entire Australian industry is growing every year, mainly due to the unproductive construction sector. To tangibly contribute to addressing this issue, it is important to first establish a commonly accepted definition for productivity and principles or theories governing productivity.

Productivity is defined as the ratio of the output volumes to input volume, where these volumes can be considered in terms of capital, investment, labour, or other factors [53]. An economic perspective considers the inputs and outputs in terms of capital [54]. Microeconomics addresses the difference between the outputs and inputs in the Production Theory [55]. Productivity also can be explained through its roots in some principles and laws in operation management. The following sections explain these theories and concepts.

### 2.1.1 The economic perspective

*Production theory* is the study of production or the economic process of converting inputs into outputs. Production is defined as the process of combining material and immaterial inputs to make an output for consumption. According to production theory, each firm's objective is to maximise its profits [54] in the production process. This profit itself consists of two parts; (i) revenues, and (ii) costs. Supposing that the firm produces $n$ outputs $(y_1, \ldots, y_n)$ and uses m inputs $(x_1, \ldots, x_m)$, the prices of output goods are $(p_1, \ldots, p_n)$ and the prices of inputs are $(w_1, \ldots, w_m)$. The profit that the firm receives, $\pi$, is expressed as:

$$\pi = \sum_{i=1}^{n} p_i y_i - \sum_{i=1}^{m} w_i x_i \tag{2.1}$$

The first term is revenue and the second term is cost. This equation implicitly refers to both leverages that the MC utilises to increase a firm's profitability. The first term can be increased by increasing customisation, and the second term is reduced when production processes are optimised.

#### Maximum revenue

The *Consumer demand theory* tries to relate the customer's preference of goods and services to their costs [56, 57]. The economic conception behind consumer behaviour is quite simple, meaning that people choose the best things they can afford. For instance, if two product options exist, the customer ranks them based on their desirability. That is, the customer either determines one of the options that is clearly better than the other or decides that the two options are not significantly different in terms of the desired functions expected from the product and that does not justify the price difference. Customers naturally make choices to maximise their "utility", that is, to make themselves as happy as possible [57]. Utility is an indicator of the customer's preferences and has also been cited as "well-being" in the economic literature.

According to Chamberlin's *Theory of monopolistic competition* [58, 59, 60], customers try to maximise the incremental utility of a good that satisfies their needs better than the best standard product attainable. This means they aim to attain maximum value from customisation. This utility has further been described in microeconomics by defining a utility function for every possible product choice to show how much desirable they are. The utility is also addressed using the term "value" in the construction-related literature [23, 61]. This utility was argued to be highly dependent on the individualisation of the product, in chapter 1.

**Minimum cost**

*Theory of cost* explores different types of costs associated with a firm's operations, including fixed, and variable costs. The latter best lends itself to optimisation as this type of cost will decrease if the production quantity increases. However, the production quantity can increase up to a certain point without requiring a significant increase in marginal cost. Otherwise, it would require. This is referred to as the economies of scale. Economies of scale imply that large-scale production (i.e., MP) reduces the cost of production. The idea of scale economies dates back to the 17th century when Adam Smith [62] suggested that the division of labour leads to larger production returns. By the scale of production and lowering costs, businesses may achieve economies of scale. This occurs because overall costs are distributed over a greater number of products..

*Division of labour* is the separation of a work process into a number of tasks, with each task performed by a separate person or group of persons [63]. It is most often applied to MP systems and is one of the basic organising principles of the assembly line. Breaking down work into simple repetitive tasks eliminates unnecessary motion and limits the handling of different tools and parts. The consequent reduction in production time and the ability to replace craftsmen with lower-paid unskilled workers result in lower production costs and a less expensive final product [64].

*The economies of scope* is a complementary concept to the economies of scale, which is achieved when producing a wider variety of products or services alongside each other, is more cost effective for a firm than producing more standard, or producing each good independently. Economies of scope also exist if a firm can produce a given level of output of each product line more cheaply than a combination of separate firms, each producing a single product at the given output level. Economies of scope can arise from the sharing or joint utilisation of inputs and reduce unit costs. Goldhar and Jelinek [65] mention the following advantages of economy of scope for businesses:

- Extreme flexibility in product design and product mix
- Rapid responses to changes in market demand, product design and mix, output rates, and equipment scheduling
- Greater control, accuracy, and repeatability of processes
- Reduced costs from less waste and lower training and changeover costs
- More predictability (e.g., maintenance costs)
- Faster throughput thanks to better machine use, less in-process inventory, or fewer stoppages for missing or broken parts. (Higher speeds are now made possible and economically feasible by the "smart" machines and the information management abilities of computer-aided manufacturing (CAM) software.)
- Distributed processing capability made possible and economical by the encoding of process information in easily replicable software

As evident, this concept adds the element of product variety to the former concept of *economies of scale* as an enabler of production efficiency. Enabling the company to benefit from the economies of scope highly depends on the product design and mix, which will be discussed further in the following sections. It is argued that a modular product architecture can greatly contribute to the company’s ability to achieve economies of scope and economies of scale.

Table 2.1: A summary of the economic principles

| Concept | Principles and suggestions | Applications in this research |
|---|---|---|
| Production theory | Firms should (1) decrease costs (efficient production); (2) Increase revenue (higher sales or price). | Used to formulate the production optimisation function. |
| Consumer demand theory | Customers choose the best product they can afford (price). Among affordable options, they choose based on the product's utility. | Used to formulate architectural flexibility in the mathematical model. |
| Theory of monopolistic competition | Customers gain utility from the amount of product's customisation. | Used to formulate maximum customisation. |
| Division of labour | Suggests simple and repetitive tasks, unskilled and low-paid workers, lower production time. | Used to formulate maximum standardisation, and choosing CLT. |
| Economies of scale | Producing the same thing in large scales is economically effective. | Used to formulate component standardisation. |
| Economies of scope | Suggests increase product variety while maintaining production efficiency by reducing waste, more predictability, repetitive production, and better information distribution. | Used to formulate maximum variety and minimum product waste. |

### 2.1.2 Operations management perspective

Operations management discipline has been criticised for its lack of theoretical rigour [66]. Over the years, the field of operations management has developed a set of laws that explain the productivity of operations. These principles can be called laws since in the terminology of the philosophy of science; they are either deductive and derived from mathematical foundations, or probabilistic and derived from observed data. A number of these laws are briefly mentioned and explained here, and if possible, connections between these laws and theories are established.

- *Law of variability:* "Greater random variability, either demanded of the process or inherent in the process itself or the items processed, reduces productivity." [67]. This law is based on queuing theory itself and has been verified through simulation Conway et al. [68].
- *Law of bottlenecks:* "An operation's productivity can be improved by better management of its bottlenecks. If a bottleneck cannot be eliminated, productivity improvement can be achieved by maintaining consistent production through it, if need be, with long runs and few changeovers." [67]. This law is associated with the theory of constraints [69], whose foundations are not empirical but rather mathematical and verifiable by simulation. The main idea behind the theory of constraints implies that every process has a constraint (bottleneck). Making efforts to improve this constraint is the shortest path to gaining more profits.
- *Law of quality:* "Productivity can frequently be improved as quality, i.e., conformance to specifications, as valued by customers is improved and as waste declines, either by changes in product design or by changes in materials or processing." [70]

- *Law of factory focus:* "Factories that focus on a limited set of tasks will be more productive than similar factories with a broader array of tasks." [71]
- *The theory of swift, even flow:* "The more swift and even the flow of materials through a process, the more productive that process is." Thus, the productivity for any process (e.g., labour, machinery, material or total factor productivity) increases with the speed of material flow through the process and decreases with increases in the variability associated with the flow. This variability can be associated with the demand on the process or with steps in the process itself. This theory is general and inclusive since each of the previously mentioned laws contributes swiftness and evenness of the flow of materials through production processes [67].

The *swiftness* of flow can be increased by eliminating or reducing non-value adding, or wasteful, processes. According to Hall and Hall [72], seven types of waste can occur in the processes:

- Overproduction
- Waiting
- Transportation
- Unnecessary processing steps
- Stocks
- Motion
- Defects

Eliminating bottlenecks, which is captured by the concept of throughput time, or the total time spent on the materials to produce the final output.

*Evenness of flow* can be achieved by decreasing variability in (1) the demand on the process, or (2) the process's operations steps. The variability, therefore, can be measured in each of the following forms:

- The time gap between different demands
- The quantity of demands
- Time spent in different steps of the process

Table 2.2: A summary of operations management principles

| Concept | Principles and suggestions | Applications in this research |
|---|---|---|
| Law of variability | Decrease variability in product and production processes; standardise | Used to formulate the standardisation function |
| Law of bottlenecks | Eliminate bottlenecks in the production processes. automating the design as the first bottleneck helps with productivity | Choosing design optimisation as the research focus |
| Law of quality | Increase quality; less wasteful production processes and better conformance to the customer requirements to create value | Used to formulate standardisation and customisation objectives |
| Law of factory focus | Standardisation of production tasks, which can be created by standardising the product itself | Used to formulate components standardisation |
| Swiftness of flow | Design standardisation can improve swiftness by decreasing waiting time, throughput time, stocks, defects, motion and transportation | Used to formulate standardisation to improve material flow |
| Evenness of flow | Design standardisation can create similarity in both on-site installation activity times and off-site production processes for parts. | Used to formulate standardisation to improve material flow |

A summary of the principles presented in this section, regarding their applicability to this research is presented in Table 2.2 and Fig. 2.1. In the next section, the improvements that are claimed in Table 2.2 will be verified through a literature review, and design guidelines to make these improvements will be extracted.

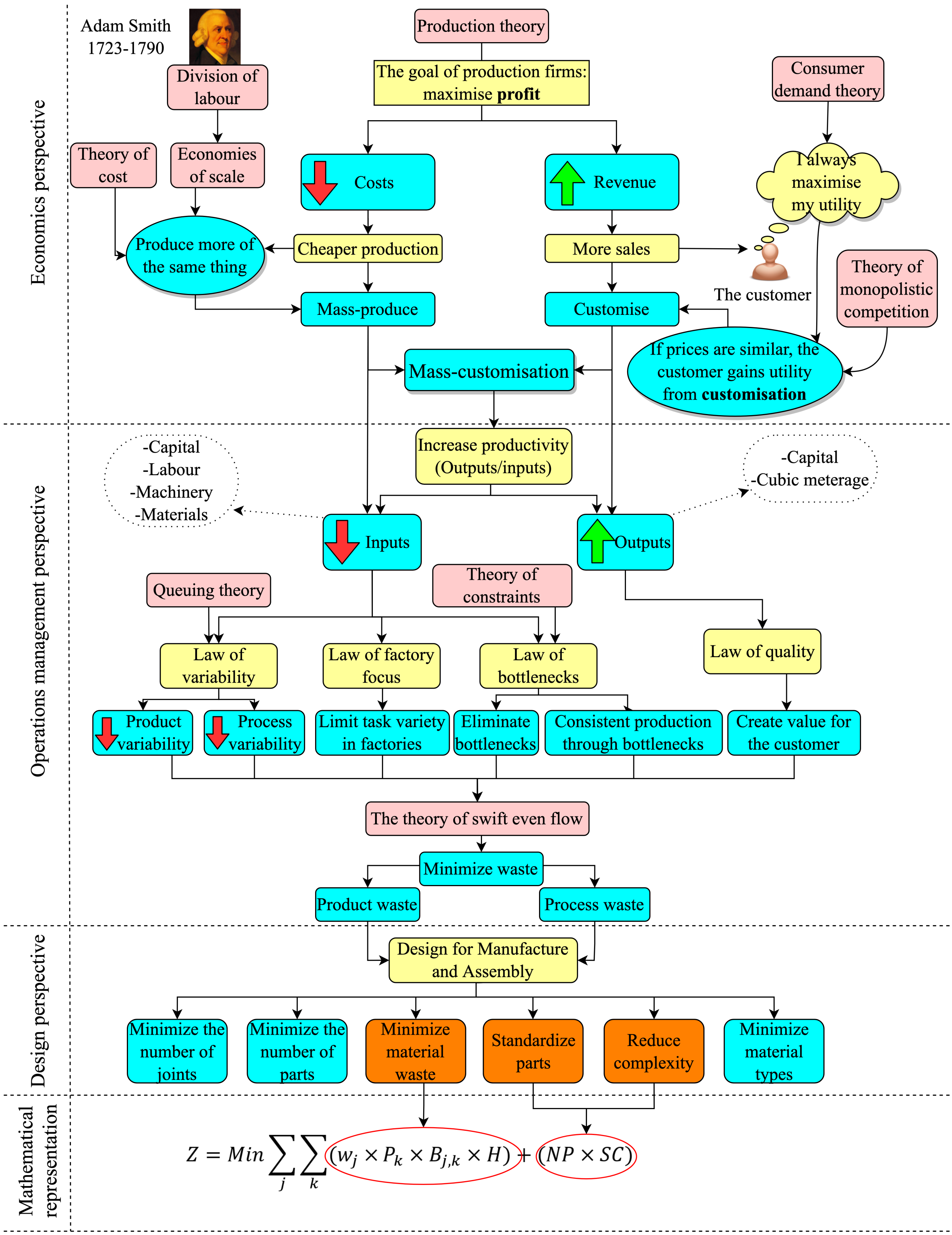



Figure 2.1: A summary of theories and concepts leading to the formulation used in chapter 4

## 2.2 MC as a response to the productivity issue

This section first discusses the essential characteristics of MC strategies that make them a proper response to the low productivity issue. The discussion efforts to establish a connection between the characteristics of MC enumerated in the literature, and the theoretical operational and economic solutions to the productivity issue discussed in the previous sections. Then, the discussion progresses to concepts and practices in the MC literature, with a view towards their applicability to the problem of the current research.

- **Customer focus**

One of the main characteristics of the MC strategies that distinguish it from MP is its focus on the customer [4, 26]. Nagel and Dove [73] stated that the 21st century's consumers don't see quality as reliability anymore and have learned to take it for granted over time. Thus, value for the consumer must be realised through the conformance of the product with each customer's specific needs. However, the industrial nature of the MC production methods will also increase the customer's satisfaction regarding more basic factors such as price [74] and technical reliability. This fact becomes more important in volume industries that manufacture based on the order (Make-To-Order (MTO)) such as construction, by reducing the production throughput time, and quick delivery.

Companies that implement MC strategies provide value for the customer by giving them a range of options to choose from [75, 76]. These options can involve different attributes of a product, and a range of options for that attribute, for example, a range of items (red, green, blue, etc.) can be offered for the colour attribute. da Rocha et al. [77] used the term "customisation unit", a set of customisable attributes and the range of item choices offered for that attribute. Further, MC strategies provide supports for the customers to guide their decisions and define their own solutions while reducing choice complexity (choice navigation) [38].

- **Efficient production**

The main justification of MC in the construction lies within the industry's unproductive production processes, compared to other manufacturing industries [78]. Traditionally, this issue is attributed to the industry's peculiar nature [14, 79], i.e., site production, temporary organisation and one-of-a-kind product. These peculiarities can be resolved to an extent through prefabricated and offsite construction methods [80], but these methods themselves are tied to low product customisation issues, contributing to low productivity from the market's end of the value chain. This has led many industrialised construction companies to implement customer focus strategies to gain competitiveness in the market.

MC uses the modularisation concept to create product variety from a set of standard, repetitive components. Therefore, the product can be finished to a larger extent in the factory environment, offering better control and fast throughput time. Factory production also offers an opportunity to implement lean production methods, which have been extensively improved and completed for this environment. Lean production methods address waste in production operations [81] and increase swiftness in production operations, leading to productivity improvement.

### 2.2.1 MC definitions

There are several definitions for MC. In this study, we point out some of them to identify MC's aim in the building industry. Davis [11], who had predicted the emergence of MC states that "the same large number of customers can be reached as in the mass market, and simultaneously they can be treated individually as in the customised market of pre-industrial economies" [82, 83]. Introducing this strategy to the manufacturing industry, Pine has defined it as "providing tremendous variety and individual customisation, at prices comparable to standard products and services to enable the production of products and services with enough variety and customisation that nearly everyone finds exactly what they want" [26].

Tseng and Jiao (1998) have stated that MC corresponds to "the technologies and systems to deliver goods and services that meet individual customers' needs with near MP efficiency" [82, 83]. Piller [83] has identified MC as a strategy that refers to the "customer co-design process of products and services, which meet the needs of each individual customer concerning certain product features. All operations are performed within a fixed solution space, characterised by stable but still flexible and responsive processes. As a result, the costs associated with customisation allow for a price level that does not imply a switch in an upper market segment". Duray [84] describes MC as a "paradox-breaking manufacturing reality that combines the unique products of craft manufacturing with the cost-efficient manufacturing methods of mass production".

### 2.2.2 An overview of state of the art

Scholars make attempts to propose ideas, concepts, and frameworks for implementing MC and realising its outcome, i.e. productivity in different industries. As stated by Jensen et al. [39], MC helps identify differences between customers and their preferences (solution space development), efficiently reuses existing organisational and value-chain resources (robust process design), and involves the customer in the product configuration process (choice navigation). Each of these fundamental capabilities can increase productivity in different phases of construction. These three fundamental capabilities of MC were further investigated and found to be good solutions to the productivity deficiencies in the Danish construction industry as well as in other Scandinavian countries [78]. However, an essential prerequisite for applying MC principles is creating ongoing cooperation among different parties. Thuesen and Hvam [85] proposed an optimisation framework focused on optimising value and cost while handling the complexity as the central process to find the prerequisites of a successful offsite construction delivery system delivery as the case example. Combining the concepts of blue ocean strategy with platform theory, the analysis results indicated that the system delivery requires an explicit market focus, coherent modular design, value chain integration, and developing processes and configuration practices to match the product with project-specific requirements. The following subsections show that most of these requirements can be implemented in the MC context by utilising different planning, design, and knowledge-sharing methodologies in different domains. Roy, Brown [1] reported on a process re-engineering programme undertaken by one major house-building company in the UK. The company implemented a combination of new technologies, product engineering and changes in working practices to move towards re-engineering the build process. The key features of this re-engineering include product design, engineering and build, teams, business processes, SC, culture and role of the builder. Implementing MC approaches also need considerations in terms of onsite processes. Andújar-Montoya, Gilart-Iglesias [**?**] argued that focusing on an MC-based design causes infeasibility in onsite processes. Thus, they focused on developing a construction management framework to achieve MC paradigm in traditional residential buildings. The research tries to improve process management in these projects by creating synergy among strategies, technologies, and techniques common in construction management, along with other fields such as Lean and Business Process Management and service-oriented architecture. As a business strategy, the concept of product MC covers a wide scope, including marketing, planning, design, manufacturing, assembly and supply of the product [13]. Based on the above studies, in terms of the product structure, a majority of the literature uses the modularisation concept as an assumption. Modularisation is mentioned as a prerequisite for creating variety from commonality and handling complexity in this process. Below, we will briefly look at modularisation and platform strategies as one of its sub-groups.

**Modularisation**

Modularisation is defined as the clustering of various product sub-systems or components into modules to enhance the product system's flexibility [86, 87]. In the literature, modules have been defined as common, standard and compatible parts with specific functions [88, 89]. Mixing and matching these parts in various combinations produces various products, while MP is realised by limiting the number of these modules [16]. In modular product development, the conceptual illustration of the product's physical parts, their functions and interactions is referred to as product architecture [90]. To define the product architecture, functional elements should first be arranged and then mapped to physical components. There is a one-to-one allocation scheme in which each chunk (a sub-assembly of components) is physically independent and performs only one function. Finally, interfaces between interacting physical components should be specified [91]. Modularisation tools are utilised as support in decision-making in each of these steps. The aim of these tools is to define modules that are: (i) distinct, (ii) independent, (iii) tightly coupled inside, and (iv) have standard interactions or interfaces.

Jensen et al. [92] have conceptualised and tested theories of MC through modularisation in the construction industry. Through different case studies with different specification processes, they concluded that the concept of products-in-products could help enable MC in the construction industry. Modular product architectures were found to be flexible while maintaining an acceptable level of commonality across different products. Viana, Tommelein [93] explored the concept of modularity as a solution for dealing with complex systems by illustrating how it can reduce the complexity of ETO industrialised building systems in MC companies. This research also demonstrates the need for adopting an integrated product and process-oriented conceptualisation in industrialised building systems. Finally, the paper concludes that adopting a limited set of components in modular systems can help decouple design decisions and standardise processes, thus achieving SC objectives of the MC.

The definition of efficiently designed modules can allow changes to be made in one of these modules without any required changes in other modules [94]. This will help gain benefits of mass production by minimising the changes induced by the market changes, and thus, design changes, in the production lines. However, although modularity can generally help enable MC in the industrialised housing context, employing a modular approach over traditional construction needs further examination. Through a literature review study alongside industry reviews, Azhar et al. [95] tried to determine the important factors affecting choosing either modular or stick-built construction. This research identified several effective factors, including site conditions, skilled labour, transportation, organisational readiness, schedule, budget, sustainability and design complexity. Thus, depending on conditions and objectives, the choice of the modular approach can be affected. However, this study implies the presence of early collaboration among stakeholders in a modular context will make modular construction the superior option.

Shafiee et al. [96] compared two modularisation strategies, i.e., Top-down and bottom-up, through case studies. In the top-down strategy, the whole system is broken down into its components and sub-components. On the other hand, the bottom-up approach combines the smallest to the largest components to achieve its product. Results suggest that each of these approaches can be beneficial to specific types of projects. In another research, Shafiee et al. [97] used empirical data and results of industrial interviews with experts to set a guideline on how and where to use different modularisation techniques and the expected challenges and benefits. Kudsk et al. [98, 99] performed case studies on large construction companies in Europe. These companies have a similar stepwise approach to mass customising different components. Using a top-down approach for identifying and analysing technical solutions for buildings was identified to be an efficient modularisation method.

Using modularisation terminology, a platform is defined as a basic common module or set of modules used in several product family variants [100] and is often cited as an effective strategy to deal with buildings' modules [101, 102, 103]. On the other hand, product family can be referred to as a set of products across which a cluster of modules (platform) is recurrent [104, 105].

Therefore, in a modular product context, the designer's task is usually defined as transferring the customer's needs into a design, achievable by mixing and matching several modules. These modules are usually predefined and reusable across numerous products and are kept in a limited number to achieve standardisation. However, a company's competitiveness is not achieved by focusing only on the product; MC and processes should also be in alignment to achieve the full capacity of the MC.

## 2.3 Supply chain implications of mass-customisation strategies

A comparative study between SCs of construction and aerospace industries also shows fragmentation as the main problem in the construction SC [106]. Industry interviews with practitioners of both sectors indicate that there are different views towards Supply-Chain Management (SCM) in construction, in contrast with aerospace where interviewees consistently emphasised the importance of a single goal, being global competition. It is argued that global competitive pressures have caused the UK aerospace sector to get consolidated.

A major issue that slows the traditional building industry in realising MC's benefits is the high number of SC players and their conflicting values. According to the typology presented by Lin and Shaw [107], construction, in its traditional form, has a convergent SC, with the following characteristics: (1) the assembling firm performs the final assembly and manufacturing processes of the product, (2) long product life-cycles, (3) early differentiation, (4) many suppliers, and, (5) few clients. The efforts made by the industry's companies to standardise processes and products are to shift this type of SC towards a more divergent one, which involves delayed differentiation and fewer suppliers. SC models can support MC on different levels customisation using different SC models [23].

In an ideal MC environment, the production SC is integrated, and every supplier is on-board with the implementation of MC strategies. Therefore, SCM practices of MC strategies are mainly concerned with information and knowledge-sharing practices among suppliers and how this information affects the production processes. As the endpoint in the downstream flow of the materials and goods, and the starting point of the information flow upstream the SC, the customer plays an important role in SCM.

### 2.3.1 Production strategies

The concept of Customer Order Decoupling point (CODP) is applied in several industries to support the integration and improvement of SCs [108]. The level of product customisation is also highly dependent on the CODP [109, 110]. CODP dictates the proportion of production processes that can be done to forecast against customer-specific proportions. Therefore, the CODP is the separation point between decisions made under uncertainty and those made under certainty [111], or in other terms, standardised and customised activities. Based on the CODP, different production strategies have been introduced in the literature based on the SC structure, using different terminologies [112, 13, 3, 113]. In this research, the concept and terminology introduced by Olhager [114] are used for descriptive purposes. Fig. 2.2 shows different production logistics and the CODP based on Olhager [114].

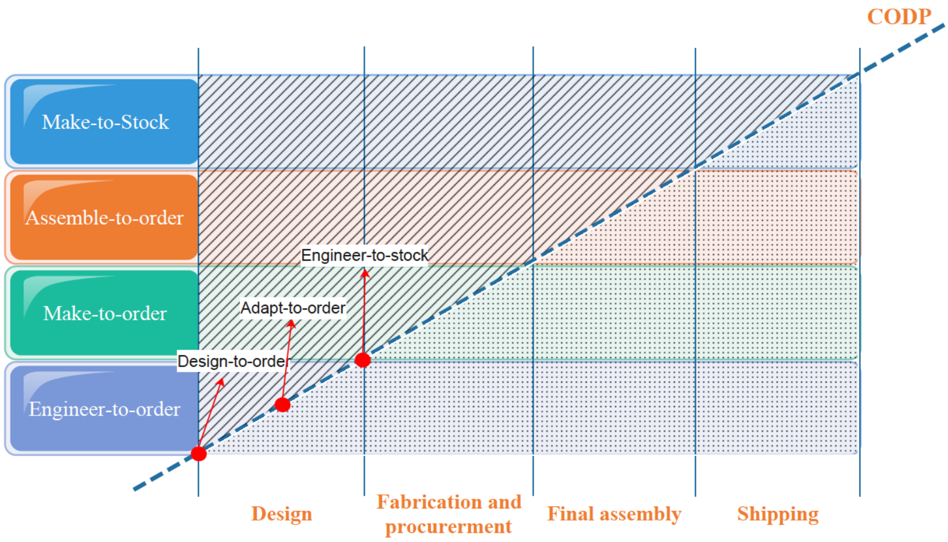



Figure 2.2: Production strategies based on the CODP

This categorisation of strategies is applicable to most manufacturing industries since the final product in these industries will not exceed a size/weight limit and usually, can be shipped as a whole after the final assembly. These products rarely need establishment processes (foundation, spacing, etc.) before being used by the end user. Even if they do, the establishment processes do not require an expert workforce and can be performed by the end users. In the house-building context, however, the final product is usually of high volume. No matter how predefined the product is, there are always some onsite manufacturing and/or assembly activities onsite.

- MTS: the production processes are performed based on the forecast and the customer information only affects the shipping of goods. Example: food and cosmetics industry.
- Assemble-To-Order (ATO): product components and sub-assemblies are finished based on the forecast but the final assembly is delayed until the customer's data are received. Example: computer manufacturers.

- MTO: the manufacturing processes are performed based on the customer's order from a set of standard designs. Example: car manufacturing.
- ETO: the product is designed and produced based on the customer's information. Example: shipbuilding industry and traditional construction.

As stated in the literature [3], traditional construction is often assumed to be an ETO industry, where the client's order enters the product development process in the engineering phase. However, building products always consist of a set of sub-products, and each of these sub-products can be produced by applying a different strategy. The peculiar characteristics of ETO industry, including onsite production, temporary production organisation, and one-of-a-kind product [79], all necessitate the integration of production processes and customer-company interactions. Hicks, McGovern, and Earl [115] conducted a survey ETO companies to identify SCM trends. The study recognised four trends in the high-volume industries, including outsourcing non-core activities to suppliers, focused operations, supplier base reduction and shifting from multiple to single sourcing, and setting long-term collaborative relations with suppliers.

As a concept that employs different processes and tools to respond to changing markets, agile production has also drawn attention as a methodology that helps attain the benefits of MC. The trends of UK housebuilding companies in implementing customer-driven strategies and SCM improvements and the barriers to the adoption of agile production have been discussed by Barlow [116]. This study investigated the principal features of agile production and its relationship to lean production principles.

Other methodologies have also shown promising improvements in the integrity of SCs. For example, multi-project approaches are claimed to lead to increased integration in the SC by Vrijhoef and De Ridder[117]. They investigated the SC integration in construction through multi-project approaches from both the supplier's and the client's points of view. It was concluded that the integration should be neither client- nor supplier-driven completely; rather, a joint approach that involves both clients and suppliers should be taken.

As an effective production strategy, the postponement has been utilised in many industries to increase the amount of standardised work, by delaying the first demand-based production activity [118, 2]. Implementing the postponement strategy in production works offers opportunities to standardise product development processes. Hsuan Mikkola and Skjøtt-Larsen [2] state that the extent of postponement depends on the modularisation of product architecture, emphasising the interrelation between the product and the SC domains. Fig. 2.3 illustrates an example of postponement, which leads to standardisation and represents its effect on CODP.

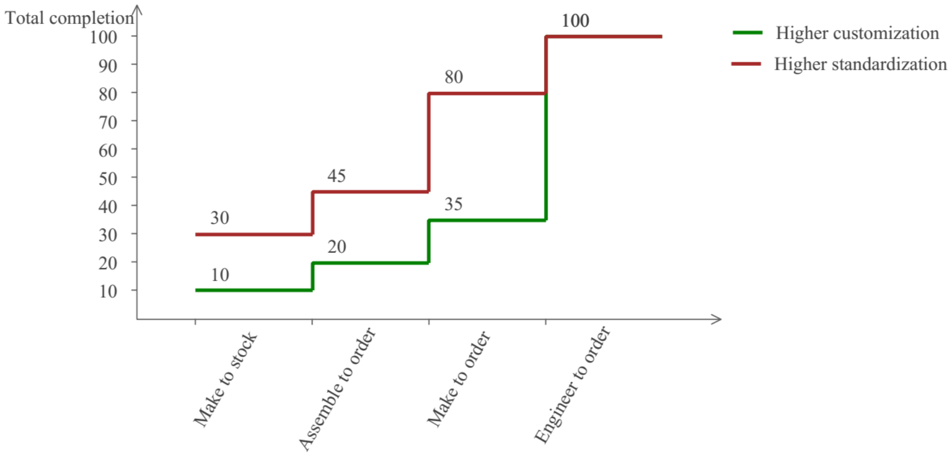



Figure 2.3: An example of comparing production strategies based on the CODP and standardisation of components in a product [3]

When implementing MC strategies in the construction industry, there can be two different approaches regarding two different industry contexts, i.e., traditional and industrialised. Moving traditional construction towards MC mostly requires strengthening the supply side of the value chain, while moving from industrial construction towards MC requires improvements in marketing and sales. Haug, Ladeby, and Edwards [119] have identified the characteristics of the transition from either ETO or mass production towards MC as shown in Table 2.3.

Table 2.3: Objectives of transition towards MC in different production contexts

| Characteristic | ETO to MC | MTS to MC |
|---|---|---|
| Product variety | Limit variety | Increase variety |
| Customer view | Create adequate variety | Create valuable variety |
| Manufacturing costs | Decrease | Slight increase |
| Business purpose | Optimise processes | Increase sales |
| Configurator challenge | Knowledge base | User interfaces |

### 2.3.2 CODP in the construction industry

The construction industry has been slow in adopting MC strategies, mainly attributed to its peculiarities in all three domains of product, process, and SC [79]. The building is a complex product, consisting of a group of sub-products, each having a specific function and its own production processes and suppliers. Unlike manufacturing, the building's production process is finished on-site, which incurs different uncertainties and inefficiencies, depending on the level of product completion before it reaches the site. Besides, the segmented nature of the building SC causes temporary relationships among suppliers for each project, with each supplier acting for their own benefit.

The type of customisation that a company offers is in strong relation with its supplier relations and processes. Traditionally, the company designs the product to order, meaning that the designer translates each customer's needs into a specific design, based on their knowledge and experience. This method usually does not allow material suppliers and builder to organise their processes based on the forecast. It moves a high percentage of product completion tasks to the construction site. This SC organisation will also force the material/component producers to employ an MTO strategy to transfer the risk of high stock levels to other players in the value chain.

On the other end of the customisation spectrum, stand the speculative housebuilders, where the design work is completely done on the forecast, and the customers are offered a relatively small and standard set of options [120]. These buildings are quite efficient in terms of production processes, but as mentioned earlier, are not appealing to the customers and are usually sold cheaply. The standard and predictable nature of the product will allow integration in the SC and standardisation in the processes. To grasp the benefits of both approaches to design and production, the product has to be produced with an optimal strategy between these two ends, which has led many companies to adopt modularisation approaches.

Modular housebuilders use hierarchical product breakdown structures to provide different levels of choice and modularity for the customer. Fig. 2.4, extracted from Barlow et al. [23], shows different production strategies based on the CODP, and the characteristics of these strategies. The strategies that best suit the goals of MC in this figure are customised standardisation and tailored customisation. These two strategies enter the customer's specification in the process of forming the final product, which is most suitable for the high customisation demand in the housebuilding sector.

Duray, Ward, Milligan, and Berry [121] also state that the mass-customisers differ in terms of their customer involvement in the design and product modularity. They introduce three types of customisation approaches, i.e., pure, tailored, and standardised customisation. They define pure customisation as designing based on customer demand from scratch. Tailored customisation is a standard basic design that is altered to each customer's specific needs. In standardised customisation, the final product is assembled from a set of predefined components. In standardised customisation, the customer enters the product design by selecting their desired features from a list of standard options.

Examples of implementing customisation strategies shown in Fig. 2.4 and the resulting SC organisations in the example case of Japanese MC companies have been shown in Fig. 2.5. In this figure, the parts of the production process performed based on the customer's needs are shown with grey colour. The product's hierarchical breakdown into parts, components, sub-assemblies, and assemblies can also be seen in this figure. Further, the designer's role in these structures is either responding to the customer's needs by creating a design from mixing predefined parts or designing a variety of sub-assemblies that are combinable in maximum permutations to create a variety of assemblies and final products.

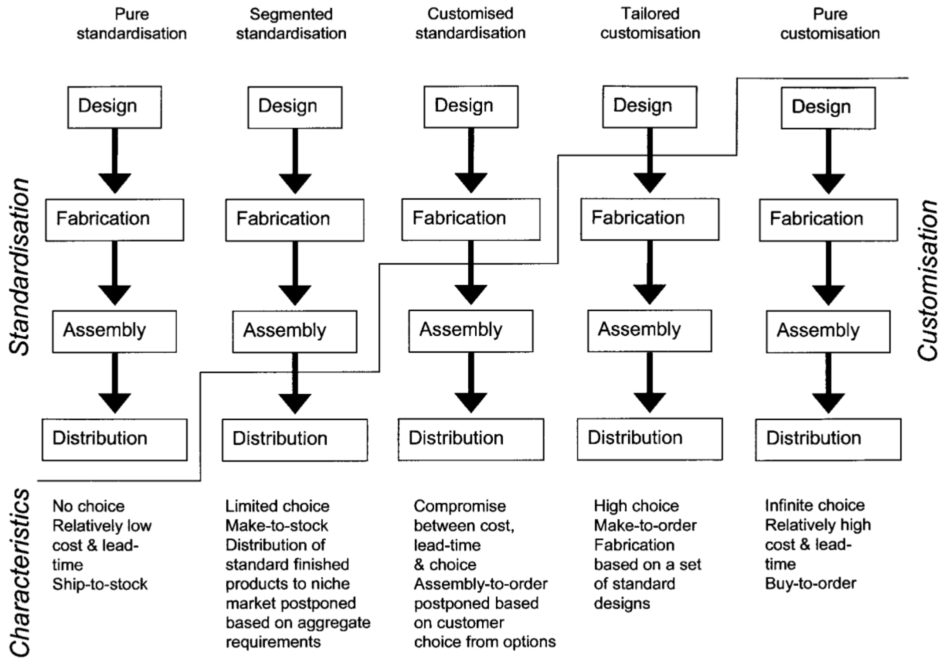



Figure 2.4: Customisation strategies based on the CODP [23]

In either of the MC cases discussed above, there is a strong emphasis on the role of the factory producers that supply finished parts, components and sub-assemblies to the construction site for the final assembly. The companies have introduced a high level of standardisation for kitchen and bathroom sub-assembly, and have integrated material suppliers with the contractors to reduce the lag between order placement and supply as much as possible [122]. This integration requires large-scale companies with a high level of market share to achieve economies of scale and scope [123].

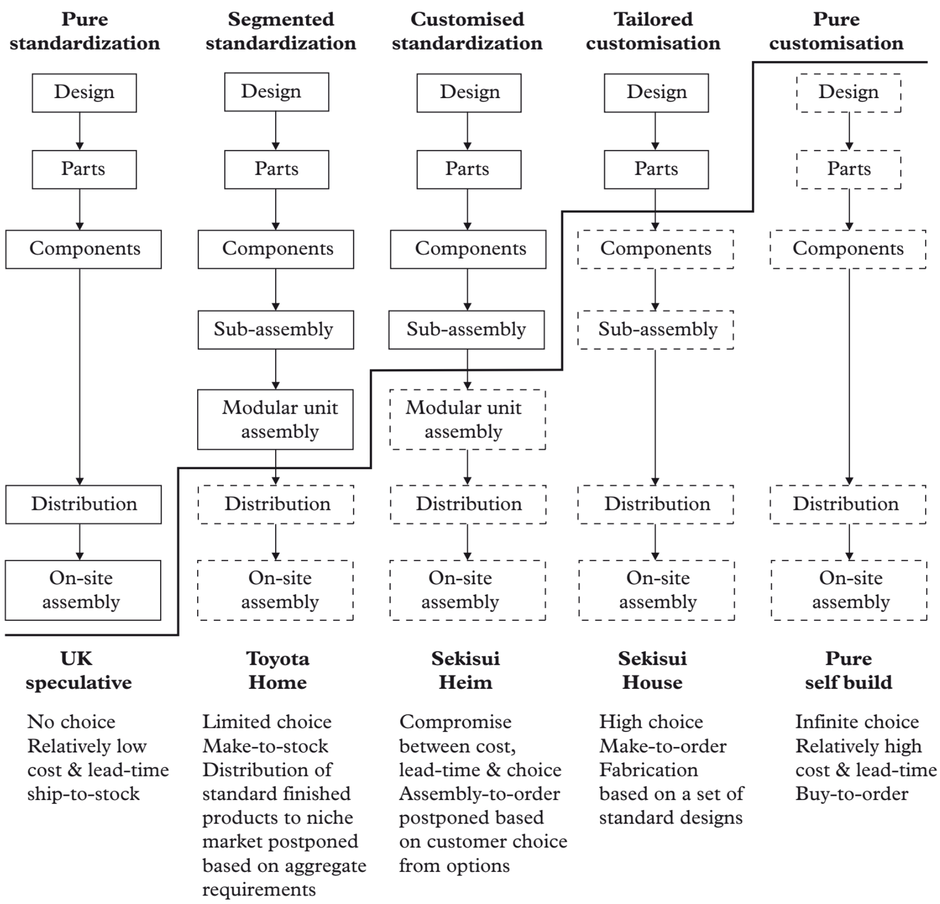



Figure 2.5: Generic SC strategies applied to the housebuilding industry [27]

The layout of the housing units, which provides spaces as one of the main functionalities for the customer [14, 27], should be highly made up of predefined components. This is where a large company with a nation-wide market share has an advantage over small companies since they can leverage the size of their operations and define a larger set of sub-products without compromising on the benefits of scale economies, through late product configuration. This larger set will, in turn, enable designers to create a wider variety of final layouts, and provide the customer with a higher level of choice, and in turn, expand their market share due to this product variety. In many construction contexts, including the Australian industry, firm sizes are not large enough, for example, Lendlease has a 2% market share while ABN and Bechtel Australia have less than 1% [124]. Compared to the case of Japanese housebuilders, where five major players share 80% of the industrial housebuilding market [7], these numbers are relatively small. Therefore, collaborative integration [125] has to be implemented through information exchange and applying the knowledge from the process and SC domains in the product domain through better designs.

# Chapter 3

## A Conceptual Framework for Applying Mass-Customisation in Building Design

## 3.1 Overview

The purpose of MC strategies is to achieve product variety to satisfy different customer tastes while increasing the standardisation of products to gain economic benefits through industrial MP strategies. Prefabricated construction has been adopted as a valuable construction methodology to help achieve MC goals. The concept of product platforms represents a manifestation of MC is a well-known terminology in the manufacturing industry, which is yet to be strongly integrated with the building sector due to various market features surrounding customer demands and product types. The literature suggests that the design work, as a bridge between the customer requirements and the final product, plays a significant role in achieving the market benefits of variety, as well as the economic benefits of mass production. However, both customisation and standardisation of buildings are currently subjective, with little consideration of their interactions. These results in sub-optimal adoption of mass-customised solutions in building construction. In this chapter, an integrated framework for a product planning and design platform is introduced, which accounts for the costs and benefits of various stakeholders over the SC of prefabricated housebuilding projects, i.e. manufacturers, suppliers, logistics parties, designers, construction companies, and, customers. This chapter serves as the theoretical framework for automated design systems, comprising different tools and methods, each targeting a part of the SC. Such tools are presented in Chapters 4 and 6, while a practical version of the current framework is introduced in chapter 5. The framework utilises building codes and modular product planning techniques to determine preliminary product architecture. The resulting product architecture is then used as a basis for parametric design optimisation with a set of constraints and objective functions specified by different stakeholders along the SC. The stakeholders rely on a common Building Information Model (BIM) platform through which presents terminologies that are utilised in the determination of constraints and objectives. This framework can be used by designers as a decision-support system, as well as by manufacturers and construction companies to optimise their own processes.

## 3.2 Introduction

The emergence of MC strategies dates back to the late 1980s, as a response to market changes. The manufacturing industry had to adapt itself to meet customer demand for products in order to remain competitive. Until now, the manufacturing industry has successfully adopted this concept through different approaches [10]. However, the construction industry still struggles to adopt MC strategies.

Although construction companies have been increasingly implementing MP approaches through prefabricated and modular construction techniques. While such endeavours have led to high-quality and affordable housing products, there are instances that lack sufficient variety and cause customer dissatisfaction [126]. The customisation dimension of the MC is usually overlooked, which makes the cost advantage offered by MP strategies to be limited to economy of scale, and not the economy of scope. On the other hand, a considerable number of developers heavily rely on customisation of buildings with a view to retain a viable share of the market. In such cases, however, cost and time inefficiencies have been inevitable which affect not only building end-users but also the equity of entire construction SC [127].

The slow adoption of MC principles in the construction sector can be attributed to the peculiarities underlying the nature of the construction industry. These peculiarities include onsite production, temporary production organisations, and one of a kind product [79]. Onsite production makes construction activities prone to productivity and unpredictability issues, since the construction site environment is not as controlled as the factory environments. Temporary production organisations that are limited to each project lead to SC segmentation, meaning that each supplier will seek to maximise their own profit and overlook the overall project or company benefits. Finally, one of a kind building products necessitate a high number of suppliers, and makes standardisation of building systems and sub-systems, and consequently, standardisation of the processes more difficult. MC strategies try to deal with a balance between two counteracting concepts: MP and customisation [9]. MP strategies offer companies competitiveness through industrialised, common production which makes products cheaper to produce and of higher quality [6]. Customisation on the other hand, implies that the product should correspond to the customer's taste to offer them more value, and offer the building company benefits through variety in product and better market placement. Therefore, a successful MC strategy is the one that balances standardisation and customising such that the products are customised enough to attract the market and standardised enough to be produced at a cost close to that of MP.

The segmented SC in the construction industry leads to an opportunistic behaviour among different SC participants, who organise their processes without consideration of and knowledge about the rest of the participants. In more detail, the process begins with the designer's drawings which reflect architectural style and their understanding of what the customer wants. The construction company/developer then places the orders of components and materials based on this design, without an understanding of how difficult these components and materials will be in terms of production and transportation. The manufacturers will then start production based on the orders and ship the components to the site's inventory, for installation.

Lack of an integrated knowledge system to apprise everyone in this chain about all of the participants and their costs and limits still remains a gap in the literature. This knowledge problem leads to sub-optimal designs that are either too standard, thus not favourable to the customer, or too customised and costly in terms of production processes. To solve this knowledge problem, the best solution would be targeting the design work as the starting point of this chain. The design work is the phase where customisation takes place, and dictates the extent of standardisation in the SC of the building product. Moreover, all SC players should be informed about the design beforehand in order to start standardising and/or customising their processes earlier.

In this research an integrated product planning and design framework is introduced which deals with the trade-off between product commonality and variety by a modular platform approach. The framework transforms the resulting product architecture to actual Design Parameters by a design support tool and optimises these DPs based on objectives of different SC participants to alleviate the problem of segmentation in the SC. This framework uses BIM objects as a shared language among SC participants to be able to consider their parameters, variables, constraints and objectives simultaneously.

This framework will help all SC participants maximising their value, while the building production as a whole is performed more efficiently with lower costs. The design work and the SC will be informed of the manufacturing, transportation and construction costs through an interface. The

SC and designer interface allows the users to incorporate their own costs and constraints into the model, and see the data entered by the rest of the users. Later on, this interface will inform SC participants and the designer of the optimal design options in form of design catalogs, and technical details of these designs.

## 3.3 Literature review

The problem of collaboration among different participants including customers, design, and suppliers has been addressed in a number of studies [49, 12, 127]. A majority of these studies [49, 128, 129, 17] target the design work as the bridge between the customer and the developer. The literature in the area of modular construction addresses the customisation aspect through modularisation tools that map customer requirements to the functions of each module. For standardisation purposes, they utilise modularisation tools to create different products by mixing a limited set of modules in a robust-flexible manner [14].

The hierarchical breakdown of the building products in different levels, also referred to as the products-in-product concept can be utilised to apply MC principles in the construction industry [92]. Modularisation can be a useful methodology in defining hierarchical product systems which have a meaningful level of commonality and variety simultaneously. The applicability of various modularisation concepts in the construction context has been investigated in several studies. da Rocha et al. [14] proposed a conceptualisation for modularisation including different elements including (i) product architecture, (ii) module interfaces, and, (iii) operational modularisation tools.

Product architecture is the conceptual illustration of the physical parts of the product, their functions and interactions [90]. Interfaces represent the inter-dependencies among physical components and operational tools are utilised in the decision-making process regarding the architecture and interfaces. Modular product platform development is one of these tools, and it involves defining clusters of product sub-systems that are shared among a family of products, systems or sub-systems. Platform modules have loosely coupled interfaces with other modules, meaning that they can be interchangeably used in different products with minimum required changes. This feature decreases design costs associated with designing product variants as well as redesign costs imposed by unpredicted future changes. Table 3.1 briefly introduces these studies and discusses the tools that each of these studies uses to address the components based on the concept introduced by da Rocha et al. [14].

Some studies have proposed systems which involve customer in building configuration process by facilitating customer-designer or customer-company collaboration. Examples of these systems are studies performed by Frutos et al. [134] and Ramaji et al. [90] who introduced object-oriented models for the customisation of product configuration processes in MC environments. These models include hierarchies, interactions, and attributes of building modules in standard BIM file formats, which enables collaboration among different participants through a common language.

Traditionally, transforming and applying these rules into DPs in the form of design rules was assigned to the designer. Automating this process can increase design precision and speed. Previous studies address this issue by modelling the design process through design and grammars parametric design methods. A grammar comprises a set of substitution rules, applied

Table 3.1: Modularization aspects, their tools and objectives in the literature

| Aspect | Modularisation tools | Objectives |
|---|---|---|
| **Product architecture** | Module combination matrix [14] | Visually describe modules that are used across product variants |
| | Module identification matrix [130] | Identifies the possibility of clustering sub-systems into modules |
| **Module interfaces** | Dependency structure matrix [15] | Maps module inter-dependencies in a matrix form |
| | Module interaction matrix [14] | Shows the interfaces among modules |
| **Operational tools** | Quality Function Deployment [130] | Mapping customer needs into product functional requirements |
| | Product platforms [131, 3] | Clustering and decoupling common product sub-systems |
| | Generational variance index [102, 130] | Identifies platforms based on their requirement for redesign |
| | Coupling index[102] | Measures the coupling among product components |
| | Module use index [14] | Assess module commonality among products |
| | Axiomatic design [132, 133] | Minimising the dependence and information content of the design |

recursively to an original assertion in order to generate a final statement [50]. Design grammars are utilised to generate feasible and optimal design solutions. For this purpose, first a programming grammar analyses user and site data to produce design briefs, or a symbolic description of the house. These briefs are then translated to design solution by a design grammar in a language that is codified by its shape grammars. The rules that are employed to generate design grammars can be extracted from the customer through web-based interfaces [50], design guides and the knowledge of a human designer [135], and share design information on visual interfaces [6]. The process of extracting and translating a designer's knowledge into shape grammars have been extensively discussed by [136].

Parametric and generative design methods have also led to manufacturing efficiency, or a higher output/input ratio, and effectiveness which refers to the conformance of the output to the desired purpose, across the SC [129, 17]. Parametric design is a process to express parameters and rules that clearly define the link between design intent and design response. Generative design methods on the other hand, iteratively seek for the best solution to a design intent within design boundaries. Combined with visual optimisation and digital fabrication technologies, this method has been used in a collaborative web-based environment to generate mass-customised house shapes by Bianconi et al. [49].

In this chapter, a framework has been proposed for incorporating constraints and objectives of customer as well as all SC production factors in early design stages. Compared to the methods in the literature involving feedback iterations among different parties, this method can lead to reduced time-loss and design defects the design in Haller et al. [137]. The main innovation of this research is to incorporate variables from all SC players in both product architecture and design, and standardisation of the design process itself by introducing a modifiable general design platform.

Design and planning activities of a building can be manipulated to solve a considerable amount of problems arisen due to the segmentation in the SC. Each SC participant will be affected by different characteristics of the design work, and have their own specific costs and benefits which should be taken into account. To find these parameters, an extensive literature review along with industry interviews with experts in each field has been done. Results of these interviews and how our framework will address each of these issues are shown in Table 3.2. The proposed framework enables MC through an integrated product design and planning system, which uses a web-based server to communicate with all SC participants. The system receives data from different participants including the customer, designer, general contractor, transportation, and manufacturing company, and incorporates these data in the planning and design of the product through a systematic process (Fig. 3.1). In this section the framework of this system is discussed in detail.

Table 3.2: Modularization aspects, their tools and objectives in the literature

| Stage | Issue | Approach |
|---|---|---|
| **Manufacturing** | Continuous production | Component standardisation |
| | Odd geometries | Design optimisation based on components |
| | Managing storage space | Optimisation of component shapes and types |
| | Inventory management | Early provision of order information to SC |
| | Variety in orders | Minimising variety in component types |
| **Transportation** | Weight and height restrictions | Component weight and geometry constraints |
| | Trailer's unused space | Optimisation of geometries |
| | Swept path analysis | Constraining component sizes based on the site access |
| | Supplier's distance | Optimising components based on supplier's inventories and transportation costs |
| | Vehicle costs | Optimising components based on trucks |
| **Construction** | Required crane types | Optimising components based on required cranes |
| | Number of cranes required | Optimal design for minimising the number of cranes |
| | Onsite storage | Optimising component characteristics for optimal storage |

## 3.4 Product architecture

Numerous studies have emphasised the importance of optimal product planning in achieving the goals of MC. This phase is the first step of the framework's building development process since it offers a macro view of a building producer's business by planning families of products (highest decomposition level in Fig. 3.1), regardless of the design details. A prerequisite of this step is to have enough knowledge about the target market and to have defined clusters of customers having similarities in tastes (Fig. 3.2). Based on these clusters, the product families can then be defined and optimised to respond to the requirements of these clusters efficiently and effectively. Note that the product planning process is performed infrequently, and its results apply to a series of projects performed at different times and locations. So, the type of data gathered and used for the purpose of product planning and defining a family of products should have a level of consistency through time to be meaningful for its purpose.

Afterwards, the collective requirements of the cluster of customers should be extracted and mapped to different functions of product modules. The nature of modules and how they function is different in building products from other types of products since their function in the highest composition level is to provide spatial voids for the users, while components in the lower levels contribute to the purpose of the higher-level systems. Interfaces in the building product's architecture dictate how different spatial voids interact in different aspects, including space, geometry, and material. To maximise the level of customisation in a modular product architecture, modules should have decoupled or loosely coupled interfaces, meaning that they can be used across different combinations of modules.

Fig. 3.1. shows an example of platform-based decomposition of a building product to sub-products to enable product variety on different levels. Platforms can be defined on different levels to increase the level of product

standardisation, and create a variety of sub-products on higher levels, by adding, removing or substituting new modules to the platform. Note that defining the inner breakdown levels between the whole product and components totally depends on the complexity of the product and its systems. In a simple system containing no sub-systems and made out of only components, defining sub-systems and modules is not feasible or necessary.

The current framework utilises **QFD!** (**QFD!**) matrix to map customer's attributes into functional requirements and GVI to map these functions into DPs. GVI is a valuable tool to identify product sub-systems requiring less potential redesign and, thus, are better options as a platform across the product family.

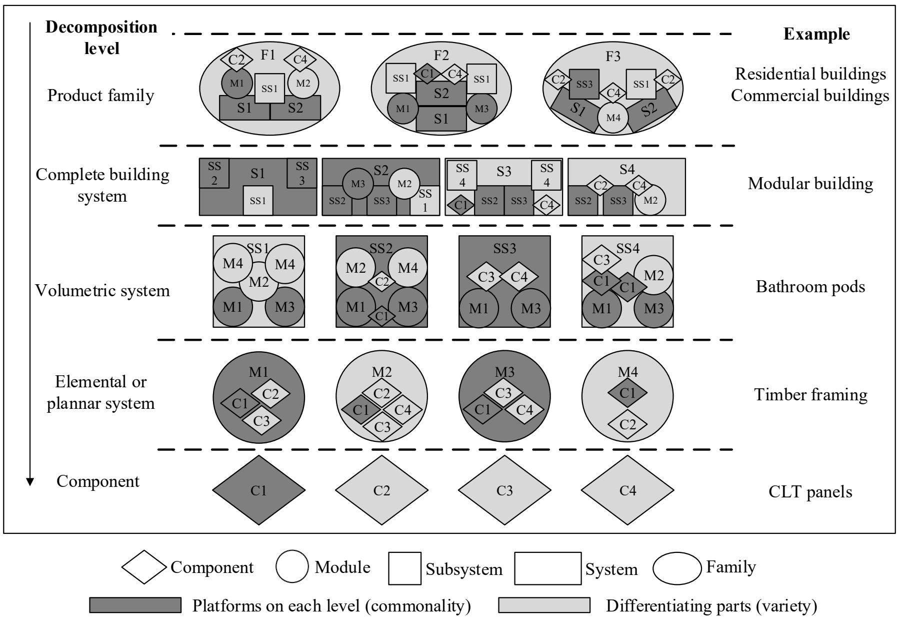



Figure 3.1: Platform-based hierarchical decomposition of a building product

## 3.5 Automated product planning platform

Having the DPs of the product family defined based on the customers' attributes, the next step will be gathering the data from other SC participants for defining the product family. These data along with the DPs obtained in the previous step, will be introduced to the optimisation platform to generate a set of optimal design catalogs conforming to these general rules. These DPs dictate the geometric and spatial rules that the building components should comply with.

Since in the building industry, organisations are usually segmented and SCs are temporary, the product planning data should be chosen such that they maintain the required level of consistency. Some of these criteria include: component specifications and their order frequency, manufacturing constraints, general building codes and transportation laws, physical limitations in terms of weight and dimensions, and rough estimates of transportation and assembly costs. These data should be applicable to the entire geographic area in which the company and their suppliers operate. Applying these rules, the system is capable of generating designs which are mass-producible and customised simultaneously. To achieve a more optimal design however, the company's engineers should add new project- and site-specific constraints and objectives. Fig. 3.1 shows a visual presentation of the information exchange in the framework at hand.

## 3.6 Automated project design platform

The main purpose of creating the abovementioned system which applies to wide range of projects and then adding some project specific rules,

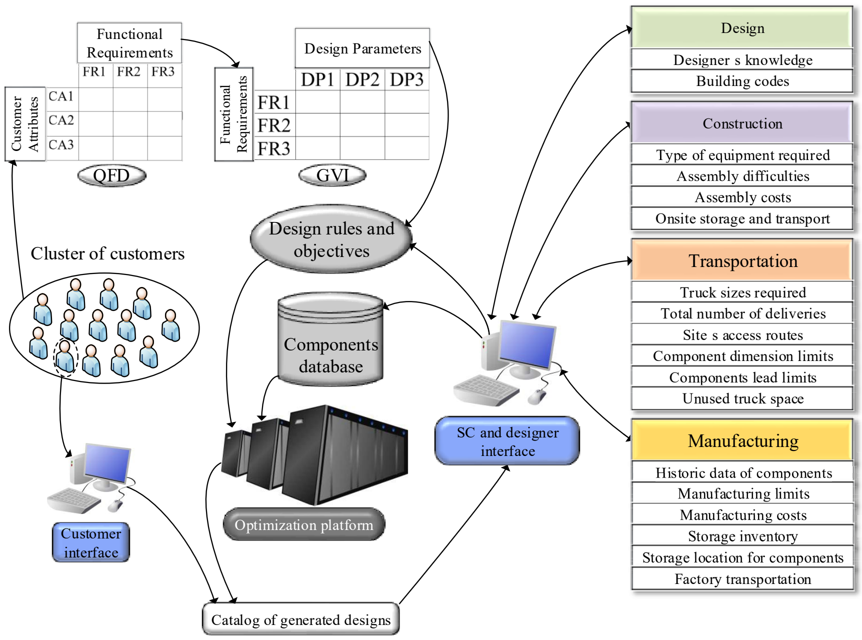



Figure 3.2: Overview of the product planning and design platform

lies within standardisation of the design process itself. This standardisation will lead to lower information and knowledge gathering/exchange requirements which itself is one of the main problems with segmented SCs, and can be time consuming.

Having the general system at hand, the precision of DPs are increased through new design rules, introduced by the designer, based on specific project conditions, as well as general contractor, transportation and manufacturers. The system allows each of these companies to introduce new rules that override the general rules, if they see necessary, but the general rules could not be overwritten.

Through a computer interface the customer is presented with a set of choices regarding the modules of the building, and their choices will lead them to a visual representation of the building which is generated on an online platform based on a BIM software. The customer's decision will be transferred to a web server to be accessible to all suppliers and contractors, providing them with an early head-start in beginning their processes.

## 3.7 Conclusions and discussion

A framework has been presented for incorporating costs and constraints of different SC participants in the design work of modular buildings. The framework uses market data and modularisation tools to develop a family of products along with their architecture. Using historic data extracted from SC players, a standard parametric design algorithm is introduced which is capable of generating feasible, mass-customised design solutions.

The framework also allows for active data exchange across the SC in the context of each specific project, to generate designs that are customised for both the customer and the particular suppliers of the project. This framework is the foundation of an integrated design system which can be used by developers in conceptual design phase to assess their options regarding the design of the product family. The project-specific system can be used by modular building developers and their suppliers to create a SC collaboration which is reflected in the design work.

# Chapter 4

## Developing a Design Support Tool for Mass-Customising the CLT Buildings

## 4.1 Overview

Low profitability of the building industry has driven the adoption of industrialised production methods in this sector. In an industrialised context, MC is a set of strategies aimed to offer tailored products at prices close to those of MP. MC can be achieved through integrating market knowledge and SC processes into the building design. Nonetheless, the MC-related literature is slim in optimising designs for such an integration. The goal is to find optimal design configurations for the load-bearing spanning systems that incur minimum product waste and manufacturing process waste. The chapter uses CLT buildings as cases of highly prefabricated systems. The preliminary layout of a building is first mathematically modelled. Then, Genetic Algorithms (GAs) are adapted to optimise wall dimensions and billet cutting plan. The example case demonstrated significant waste reduction compared to the building industry benchmarks. This highlights the practical benefits of the systematical implementation of MC from the early design stages. The present study contributes to the body of knowledge by introducing a novel design support tool that facilitates the adoption of MC in the building industry. The current tool is an example of the design optimisation platforms, as presented in the previous chapter (refer to Fig. 3.2). However, this chapter mostly focuses on the mathematical modelling and optimisation process of designs rather than the interface and issues regarding the integration of various SC participants, which were theoretically presented in the previous chapter and will be made operational in the next chapter.

## 4.2 Introduction

In its traditional form, the construction industry suffers from low productivity, which is mainly attributed to craft-based, labour-intensive production processes performed on-site [1]. Such processes have long lead-times and are difficult to control in terms of quality. In recent decades, the construction industry has begun to adopt industrialised production by borrowing the concepts from the manufacturing industry, known as a sector that has reached cost efficiency with optimal quality [138]. The industrialisation of the building product has gained attention due to the benefits it brings through economies of scale [139, 140, 141], higher quality [40, 142], waste reduction [143], time and cost-saving [144], higher productivity [145], and sustainability [146, 147, 148].

Applying industrial production concepts to the construction context can lead to significant production efficiencies. Still, where this involves high levels of standardisation, it tends to decrease product customisation, thus affecting market competitiveness. A resolution is to adopt the business strategy of MC, to respond to different market segments while still maintaining the economies of scale through MP. MC combines the contradictory goals of individualisation and cost-efficient production [129] to provide customised products or services through flexible processes in high volumes and at a reasonably low cost close to that of MP [19]. The main objective of this strategy is to balance standardisation and customisation for maximum profit.

As stated in the literature [20], MC strategies can be implemented in different areas, including marketing, planning, design, manufacturing, assembly and supply of the product. The ultimate goal is to keep the processes as standard as possible throughout the entire value chain, while the physical product becomes more specific along the chain towards a custom product for the end-user. When standardising SC processes, the design phase is of extreme importance since it is the bottleneck for further streamlining the entire manufacturing process [21]. In contrast to traditional construction, where the final product is integral from a large number of on-site activities, industrial construction breaks down the product into its forming components, manufactured in the factory and assembled on site. This modular product design is a requirement for implementing MC, where standard modules can be utilised to form custom products

In modularisation, a notion is to break down the building into a set of highly standardised components assembled to act as a core part, with a set of non-standard components around this core to form the final product [121]. "Open building" is a building design approach developed based on this idea, which simultaneously provides high levels of design customisability and standardisation. An open building lends itself to MC and consists of a core, which is also termed as "Chassis" or "Base building", and custom parts that are added to this platform, called "infill" [4, 102]. When choosing parts of the building core, the designer should consider the value that customising parts will offer the customer. The building structure offers a high potential for standardisation as the core in this system since the user does not directly interact with it [27].

Decisions regarding the building design are made at different stages, including conceptual, preliminary, and detailed design. However, a successful MC design relies on early planning of the product for manufacture and build processes, besides customer requirements [32]. Thus, the implementation of the open building notion should start early. Moreover, the literature suggests that 80% of the construction resources will be allocated based on the decisions made in the early design stages [34]. Early decisions regarding the structural system, spatial forms and the optimum location of structural members (topology optimisation) can greatly influence the build processes of the final building. Because design-related problems are inherently complex [35, 36], introducing the complexity of such processes [149] exacerbates this condition. A remedy to this complexity is the automation of design.

As one of the core capabilities of MC, flexible automation [38] uses automated processes across all production phases [39] to handle this complexity. Automating the design process decreases not only the lead time caused by errors or variations through efficient search in the design space but also assists rapid and flexible estimating prior to tender through early supplier involvement [40, 41]. Nonetheless, the literature on automating the design process tend to overlook the production and build phases. In particular, MC has not been addressed when automating the process of building design. Rather, the extant literature predominantly focuses on bringing design attributes of one discipline, for instance, architectural attributes, into the automation process [42, 43]. There are a limited number of studies that have taken interdisciplinary DPs into account of design automation [37, 44]. Such studies, however, have no allowance for production and construction processes.

This study aims at integrating the manufacturing and on-site assembly processes into the preliminary building design through structural wall component standardisation as part of the building core. It focuses on the optimum geometrical design of the structural walls, such that they fulfil structural design constraints. It should be noted that the optimisation of floor panels is not in the scope of the current study. The objective of this optimisation is to maintain a balance between two production variables, being product and process waste. Process waste has been addressed in the optimisation model in the form of component standardisation and is weighed against material waste in the manufacturing plant. Both of these variables have been incorporated in the model in the form of the costs that each will incur in the final production plan. To demonstrate the applicability of the model, the study uses CLT as a new system with significant MC potential for mid to high-rise buildings.

CLT reduces construction time, produces less waste and results in lighter buildings with higher comfort and building performance [30, 31]. It is a highly machinable material that enables the off-site production of building panels with various sizes suitable for different building layouts [32]. Besides its productivity benefits, CLT construction is being increasingly recognised as a system that has the potential to revolutionise the construction industry into a giant carbon sink [33]. The CLT case study is used to demonstrate its potential and perhaps improve the knowledge of this new form of construction.

## 4.3 Literature review

Automated layout design techniques have been used in the literature as design space exploration methods, aiming at finding either architectural or structural designs that are feasible and perform better in terms of a set of outcomes. Automated architectural layout design methods usually try to generate various feasible layouts and evaluate them in terms of architectural objectives such as maximum living space or lighting and minimum energy [49, 150]. On the other hand, automated structural layout design tools search for the arrangement and sizes of structural members that are optimal in terms of structural objectives, e.g., structural weight, eccentricity, etc. Since the focus of this research is on structural members, only the literature related to the structural layout design is discussed in the literature review section. Literature in the area of MC designs dominantly focus on design customisation, which involves methodologies to transform customer requirements into DPs [49, 133], or directly involving them in the design process [134, 151]. In terms of production processes, current studies mostly rely on knowledge sharing practices to integrate design with other processes [152, 90, 153], while the design variables are still determined through manual processes.

Some studies have addressed technical design details such as geometry and location of different building components such as beams and slabs [35, 36, 154], or the building framing system [154], using evolutionary algorithms such as Genetic Algorithm (GA) and Ant-Colony Optimisation (ACO). The design objective in these studies dominantly concern optimising structural performance variables or structural cost and plan regularity. This cluster of studies do not account for architectural design or the production variables. A few studies have exploited the potential of automated design methods to improve production processes by making better design decisions, specifically, by increasing standardisation of building components, which leads to lower process waste, and improved productivity in manufacturing and assembly stages [37, 44, 25].

Other studies, on the other hand, either integrate architectural and structural layout design as one design system or make efforts to fit the structural design into an architectural layout. Some examples include utilising a unified matrix method to optimise the spatial design of modular buildings [34], an evolutionary algorithm to optimise the arrangement of the reinforced concrete shear walls system [155] a GA to find the best performing structural configurations in a reinforced concrete wall-slab system [156], and, a design response grammar and an evolutionary algorithm to design the structural system for a given building spatial design [42]. Grammars are a set of algorithmic rules applied in a step-by-step manner on an initial statement to produce a final statement [50]. In the case of spatial design, the initial statement is the building footprint, and the design grammar includes a set of geometric operations such as dissection, connection, and extension, which will be applied recursively on the footprint to produce the final organisation of a set of spaces [136]. Evolutionary algorithms, on the other hand, follow an algorithmic process to guide a set of randomly generated solutions towards the optimum solution by iteratively evolving them [157].

A number of studies are also devoted to optimising the production aspect of the prefabricated building construction by focusing on the components production variables. Examples include a precast concrete production planning model for given components and their production sequence based on the installation plan [37], automated design of exterior panelised walls' geometry [44]. The optimisation presented by Said et al. [44] refers to the project team for decisions related to panel lengths, while in the current research lengths are one of the main variables to be optimised. Further, the heterogeneous and interrelated nature of the structural wall panels addressed in the current chapter, as well as the billet cuts and material waste, have not been addressed in this study [44].

In this research, a mathematical programming representation of the real-world model is used to define the solution space of the problem. This method is used for optimising an objective function in the presence of some constraints on the variables forming the objective function. It is well-suited for the purpose of this research and automated design in general, where design variables constrained by regulations and design intentions have to be optimised [158]. Due to the complex nature of the solution space, a GA technique has been utilised as the search method for the optimum values of the variables. Finally, the model is implemented on a test case to verify its applicability, and conclusions are drawn on the research contributions and shortcomings.

## 4.4 CLT buildings

Timber structures have drawn interests among building practitioners lately [159]. Several timber structural system options are available for various types of buildings, providing a variety of ways to optimise the needs of a specific project. CLT is a timber building system where a high level of prefabrication and simplicity of handling reduces the overall construction duration, making this building system efficient despite its higher material cost. Therefore, ease of manufacturing and assembly is an essential factor in the justification of using these building systems, and the structure, as an expensive and time-consuming part of the production processes, becomes a prominent area for focusing design efforts.

CLT buildings have structural characteristics similar to that of precast concrete buildings. These buildings are constructed by the assembly of prefabricated CLT panels, which are cut and processed in the factory and transported to the site for assembly. Fig. 4.1 illustrates an example of CLT panels and buildings from different views. CLT panels go through different manufacturing processes in the factory that have been thoroughly discussed by Orlowski [159]. The first station in the production line is the sawing and cutting station, which is automated through utilising CNC machines.

(a) (b) (c)

Figure 4.1: CLT panel (a), CLT assembly from the inside (b), and outside (c) [160]

CNC machines are the automated alternative to traditional manual labour-based sawing processes and are able to process large amounts of timber with higher quality and precision, straight from Computer-Aided Design (CAD) software. Costs associated with machining processes are the following:

- Cutting/processing/machining time
- Cutting tool's life
- Program setup cost
- Maintenance cost
- Staff costs
- Energy consumption

Standardisation of components to be cut with the CNC machine will reduce the program setup cost and machining time for a series of different panels to be cut since reprogramming the machine will be necessary less frequently. In turn, it will reduce the lag time, as well as costs associated with the specialist CNC operator, who will be spending less time on the CNC machine setting it up for different types of cuts and loading a new cutting program on the machine's controlling computer.

CLT structures comprise walls that support vertical and lateral loads, as well as floor panels that support floor loads and act as diaphragms to transfer

Figure 4.2: Example of CNC machines

loads to the core or bracing elements (i.e. shear walls) [161]. For each storey, the floor panels should be placed in a way that they cover the entire floor area, and the structural walls should be positioned on the lower level floor panels such that they support all floor panels. In the preliminary design stage, the sizing of these structural members is performed based on span tables provided by national codes or recommended by CLT manufacturers. The latter one complies with national codes. The arrangement of floors and wall panels on each storey will look similar to Fig. 4.3. When designing the layout of a timber building, multiple approaches can be taken, ranging between the following extremes [162]:

- Start with the timber structural system and fit the architectural layout to the resulting structure.
- Start with the architectural layout and optimise the structural design based on that design.

The approach of this research for solving the load-bearing wall layout problem will incline towards structural design by considering structural component geometries as the main variable while involving the architect by implementing their constraints on the wall design. This assumption will not limit the architect's design freedom, as it still leaves the decision about the span lengths to the architect. This approach allows the architect to define a range for the wall lengths, which are the horizontal dimension shown in Fig. 4.3. At this stage, the model will only define the horizontal dimensions of the large rectangular areas depicted in Fig. 4.3. based on the architect's suggestion. Architectural details such as the arrangement of units and room layouts will then be freely fit into these large rectangles by the architect.

As evident in Fig. 4.3., the location of load-bearing walls and the floor spans are highly interdependent, and with the assumptions made for this research, the spans specified by the architect will dictate the location of the load-bearing walls. Other cases in practice can be different; when the architectural design is completed first, the spans will be dictated by the potential load-bearing wall locations. The options to be considered when laying out the floor system are the floor span direction and its continuity. The load-bearing walls will usually be the external walls, walls between apartments, and lifts and stair shafts in the final design. Floor panels will span between these load-bearing walls in the shortest possible distance to minimise the floor depth. If load-bearing walls are designed to be parallel and unidirectional, then the floor panels can all span in the perpendicular direction; conversely, if they run in both directions, then the floor panels can also span accordingly.

Most of the flooring systems used in Mass-Timber (MT) structures are one-way spanning panels. In the case of CLT floors, the spanning capacity is in both directions; however, one direction has significantly higher strength and stiffness. Therefore, for the purpose of this study, we assume that the load-bearing walls are parallel, and floor panels span in one direction between every two adjacent walls. The building floor plan is assumed to be rectangular for simplicity of design conceptualisation, and external walls are assumed to be load-bearing in the direction parallel to the internal load-bearing walls, in this case, i.e. the longer dimension of the building floor plan.

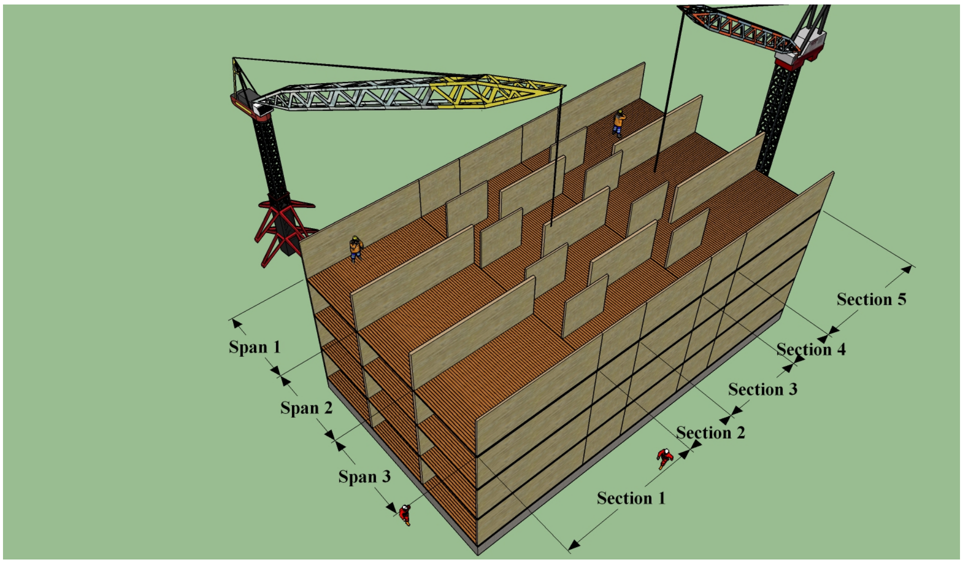



Figure 4.3: Illustration of CLT panelised structural system

Fig. 4.3. shows a hypothetical panelised system where vertical loads are only imposed on the walls in the east/west direction, and walls in the other direction (not shown) take lateral loads only. The floor plan has been divided into sections and spans to facilitate the conceptualisation of the topology optimisation problem. In this research, the word "section" is mentioned; it addresses a segment of the floor plan containing a group of walls of the same length. Span lengths will not be a variable in the current optimisation problem; however, a brief discussion is provided below about them and their implications on the current problem.

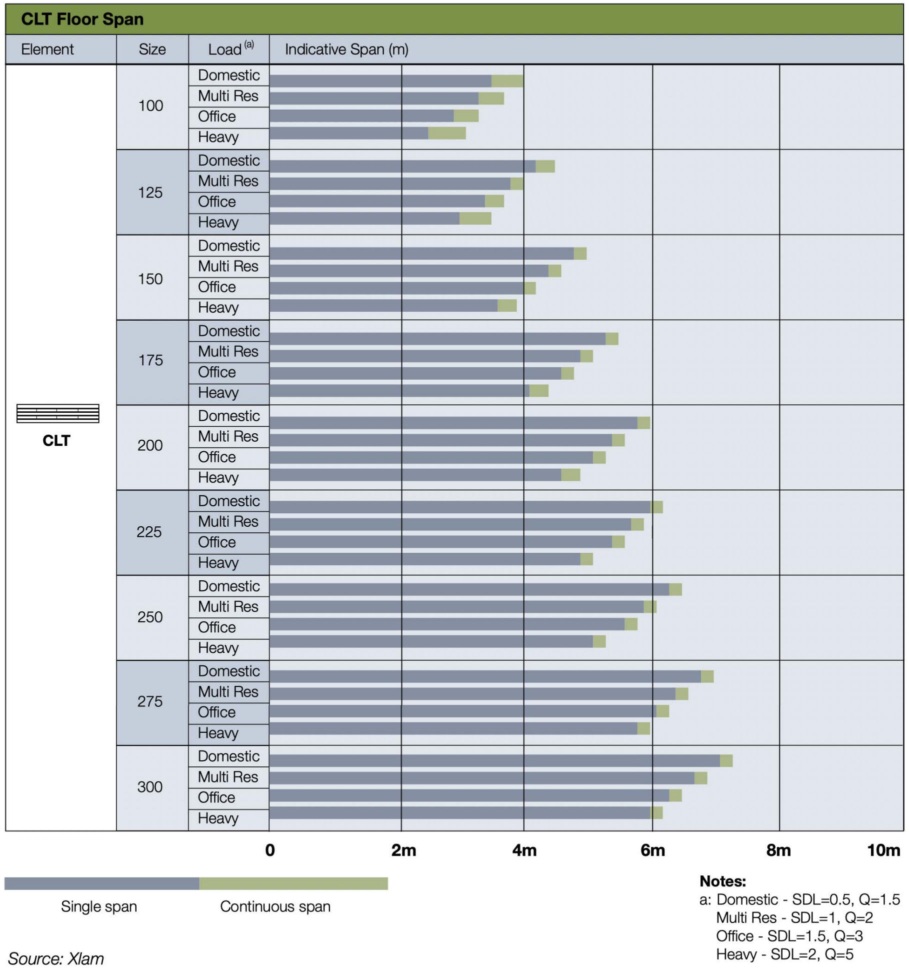
### 4.4.1 Preliminary design of the member cross-sections

In the preliminary design stage, CLT floor panels are designed based on the span length and the indicative span-to-depth ratios. These panels can be designed to be simply supported or continuous-spanning plates in the principal spanning direction. Continuous spanning floor systems are suggested to be used as they provide more robustness and earthquake capacity while allowing shallower floor depths [162]. This will also reduce the total number of floor panels used, which will incur a fewer number of lifts and reduce the time of installation operations. Based on the span length and the number of layers, floor panel thicknesses can be extracted from Fig. 4.4a [163].

After the selection of the panels, the wall is sized based on the floor panel's self-weight and its attachments (acoustic, fire resistance plasterboards, framework), and the forces applied by the above elements (either structural walls or the roof), as well as the vertical live loads based on the building class. Note that in the preliminary design stage, the wall sizing is performed based on the superimposed loads, and the more precise design considering lateral loads will be done at the engineering stage. The preliminary stage mainly involves architectural design activities, which inevitably require an initial design of the structural elements, including their locations and sizes. This design, which is performed using simple tables provided by the suppliers, will be useful for early contractor involvement.

Standard panel sizes and their specifications can be found on the manufacturers' websites, or the self-weight can be calculated by multiplying the volume by the CLT panel's density ($465 kg/m^3$). These forces are all applied on areas, which are divided equally between both wall panels supporting them, or in 3/8 and 5/8 ratios in the case of continuous spans. When the total load on each wall is estimated, using the rules above, the wall-size can be chosen using the suppliers' pre-analysis axial capacity tables, as shown in Fig. 4.4b. This figure shows the maximum span lengths that each panel designation can support, based on superimposed dead and live loads.

Some simple rules of thumb that should be kept in mind when positioning walls in a section, or in other words, designing floor spans include: (1) Walls should be positioned in a way that they allow consistent and uniform spans supported by them to avoid differential displacements at the junctions, and allow for more standard wall sizes, (2) Load-bearing walls should be sufficiently long enough to allow maximising the potential for bracing elements [162]. The length of the load-bearing walls is the main variable of the optimisation problem presented here.




(a)

| Panel Designation | Layer 1 (mm) | Layer 2 (mm) | Layer 3 (mm) | Layer 4 (mm) | Layer 5 (mm) | Layer 6 (mm) | Layer 7 (mm) | Total Thickness (mm) | Selfweight (kPa) |
|---|---|---|---|---|---|---|---|---|---|
| **3 Layer Panels** | | | | | | | | | |
| CL3/85 | 20 | 45 | 20 | | | | | 85 | 0.4 |
| CL3/105 | 35 | 35 | 35 | | | | | 105 | 0.5 |
| CL3/115 | 35 | 45 | 35 | | | | | 115 | 0.6 |
| CL3/125 | 45 | 35 | 45 | | | | | 125 | 0.6 |
| CL3/135 | 45 | 45 | 45 | | | | | 135 | 0.7 |
| **5 Layer Panels** | | | | | | | | | |
| CL5/145 | 35 | 20 | 35 | 20 | 35 | | | 145 | 0.7 |
| CL5/160 | 35 | 35 | 20 | 35 | 35 | | | 160 | 0.9 |
| CL5/175 | 45 | 20 | 45 | 20 | 45 | | | 175 | 1.0 |
| CL5/195 | 45 | 35 | 35 | 35 | 45 | | | 195 | 1.1 |
| CL5/205 | 45 | 35 | 45 | 35 | 45 | | | 205 | 1.2 |
| CL5/225 | 45 | 45 | 45 | 45 | 45 | | | 225 | |
| **7 Layer Panels** | | | | | | | | | |
| CL7/245 | 35 | 35 | 35 | 35 | 35 | 35 | 35 | 245 | 1.3 |
| CL7/265 | 45 | 35 | 35 | 35 | 35 | 35 | 45 | 265 | 1.4 |
| CL7/275 | 45 | 35 | 35 | 45 | 35 | 35 | 45 | 275 | 1.4 |
| CL7/295 | 45 | 35 | 45 | 45 | 45 | 35 | 45 | 295 | 1.6 |
| CL7/315 | 45 | 45 | 45 | 45 | 45 | 45 | 45 | 315 | 1.7 |

(b)

Figure 4.4: Indicative span for CLT floor panels [163]

### 4.4.2 Section design

The problem of designing the sections, shown in Fig. 4.3, arises when the design should account for off-site production factors as well as on-site factors. Each section in this floor plan represents the length of a group of structural walls, each having a specific size. The differentiation of these sizes will be minimum, and they will be more standard if the span designs are more standard, following the first abovementioned rule of thumb. Since each of these wall panels has to be cut from another larger panel (billet), and for many manufacturers, the shorter dimension is the stronger dimension, as shown in Fig. 4.5, the overall amount of waste on billets of different sizes will become important; therefore, it has been used as one of the main variables in this chapter.

In this research, two well-known optimisation problems i.e. Cutting Stock Problem (CSP) and Bin Packing Problems (BPP), have been taken into consideration for modelling the wall design problem. Therefore, section 4.5 briefly discusses how each is utilised in developing a mathematical model for structural wall design. Then, section 5 discusses the process of mathematically modelling this problem and defines the solution space, the variables and their constraints, and the objective of the optimisation problem. Section 6 then thoroughly discusses the evolutionary search technique used for the purpose of optimisation. Finally, the developed methodology is applied to a hypothetical case in section 4.8 to verify its applicability.

## 4.5 The Cutting Stock and Bin Packing problems

In operations research, there is a set of well-known problems, called the CSP, which optimise the material usage when cutting standard-sized pieces of stock material into smaller pieces with specific sizes. A similar type of problem, which is mainly seen as the optimal usage of limited spaces, is called BPP, where a number of items with different sizes are to be packed in a finite number of bins with specific capacities. The objective of BPP is to find the best arrangement of items where the minimum number of bins have to be used. The mathematical formulation of these problems is discussed in the following.

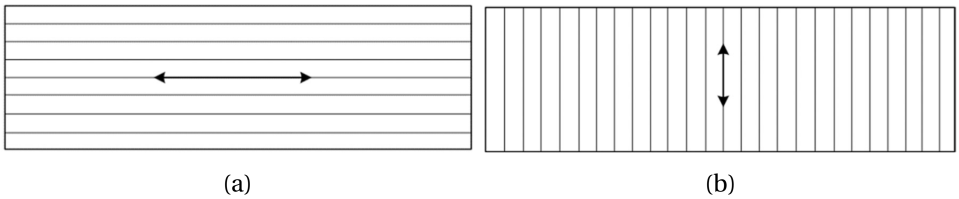


Figure 4.5: Different types of CLT billets: (a) Longitudinal panel, typically used for floor and beams, and (b) Transverse panel, typically used for wall panels

### 4.5.1 The cutting stock problem

The mathematical representation of the one-dimensional CSP (1D-CSP) [164], which in its simplest form, is provided below:

$$MinZ = \sum_j y_j. \tag{4.1}$$

Subject to

$$\sum_i w_i x_{ij} \leq c y_j. \tag{4.2}$$

$$\sum_j x_{ij} = 1. \tag{4.3}$$

In this model, sets $i$ and $j$ represent the order number and the stock number, respectively. Parameter $d_j$ represents the stock length, $w_j$ is the stock waste, $s_i$ is the order length, and $n_i$ is the number ordered cuts with $s_i$ length.

Variable $x_{ij}$ is an integer showing the number of orders with $s_i$ length cut from stock $j$, $y_j$ is a binary variable showing if stock $j$ is going to be used in the cutting plan or not, and finally, $T$ represents the sum of cutting wastes in the cutting program. Eq. 4.1 is the objective function of the optimisation problem, which is to minimise the total stock waste. Eq. 4.2 implies that the total number of cuts with length $s_i$ across all stocks must be equal to the number of orders. Eq. 4.3 suggests that the length of each stock piece is equal to the summation of all cuts made on that piece plus the amount of waste on that stock piece.

### 4.5.2 The Bin Packing Problem

Mathematically, BPP [165] can be presented, as shown below:

$$MinZ = \sum_{j} y_j. \tag{4.4}$$

Subject to

$$\sum_{i} w_i x_{ij} \leq c y_j. \tag{4.5}$$

$$\sum_{j} x_{ij} = 1. \tag{4.6}$$

In this model, sets $i$ and $j$ represent the index of each item and each bin, respectively. Parameter $w_i$ denotes the weight of each item, and c represents the capacity of each bin. Variables $x_{ij}$ and $y_j$ are both binary variables, indicating if item $i$ is assigned to bin $j$, and if bin $j$ is going to be used, respectively. Finally, $Z$ is the total number of bins that have to be used.

Eq. 4.4 is the objective function, which aims to minimise the total number of bins used in the current packing pattern. Eq. 4.5 is the capacity constraint, implying that the total weight of the materials packed in each bin must not exceed the capacity of each bin. Finally, Eq. 4.6 implies that each item must be packed exactly once across all available bins. In the next section, the nature of the problem at hand is discussed, and its similarities and differences with CSP and BPP are enumerated.

### 4.5.3 The structural wall design problem

The problem of designing the length of each section shown in Fig. 4.3 can be modelled as a 1D-BPP for a number of reasons that are discussed in this section. The first matter that should be discussed around this subject is how a problem of two-dimensional nature can be reduced to a one-dimensional problem. The answer lies within the manufacturing and transportation characteristics of these structural elements and the constraints they impose on the real-world solutions of the problem.

After the wall thicknesses are designed for the MT structure based on the spans, the remaining two dimensions of the structural walls are still to be determined. The height dimension is designed based on the floor-to-floor heights, which is constrained to a minimum due to architectural considerations (natural ventilation and daylight access), e.g. 2.7m in New South Wales, Australia. This minimum is large enough that it does not allow for utilising the billet's inevitable waste in the height dimension for another structural wall. Note that the CLT billets provided by most manufacturers have maximum widths of 3.5m. Further, structural walls are usually cut out of a billet with a width equal to the wall height to avoid unnecessary wastes.

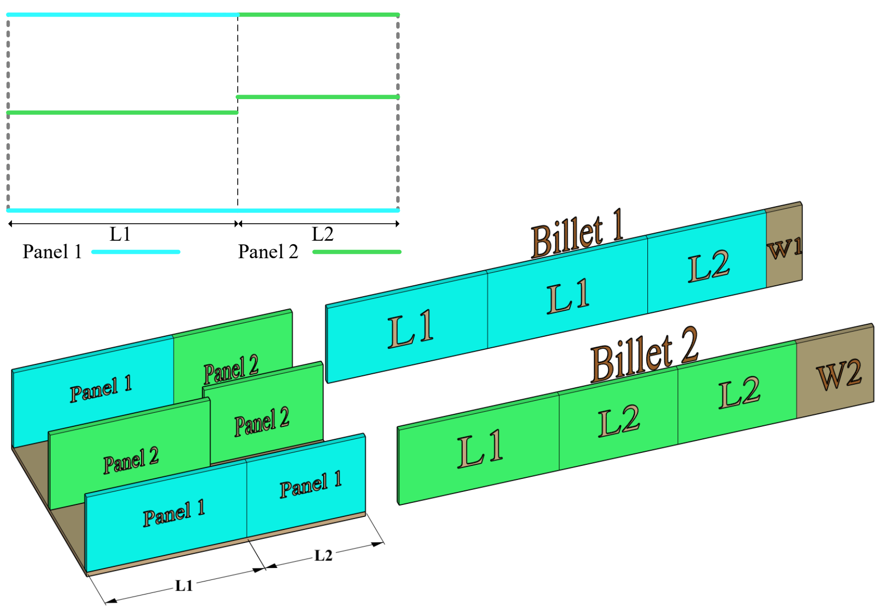



Figure 4.6: Illustrative example of a structural floor plan in 2D (top left) and 3D (bottom left), and billet cuts based on the wall lengths

Fig. 4.6 shows a simple example of a hypothetical floor plan with only two wall sections, each having three interior structural walls and four spans. There are two different wall thicknesses in this floor plan, shown by colours green and blue, and each of them should be cut out of a distinct billet. Lengths W1 and W2 are the amounts of waste that could be managed by either changing the section lengths or changing the cut arrangements across different billets of the same size, which is the main objective of a 1D-CSP.

When assuming the section lengths as constants, the problem at hand can be modelled as a 1D-CSP with different stock materials [166] 1D-CSP is NP-hard in terms of computational complexity [167], meaning that it cannot be solved in polynomial time via currently available computational facilities. In the case of having different types of materials, the problem can be addressed by solving separate instances of the CSP for each material type. However, solving the current problem requires introducing another variable, which is the section lengths. This will eliminate our previous assumption about order lengths and imposes even more complexity to the solution space of the problem.

The other difference that distinguishes the current problem from CSP and BPP is the nature of the objective function. As mentioned earlier in this chapter, the objective of this study is to optimise the structural design regarding the design MC. Since architectural design, which involves the customisation part of the MC strategy, is not the focus of the research, the emphasis will be on the optimal production processes. In the next chapter, the problem is presented in a mathematical form.

## 4.6 Mathematical representation of the model

In this section, the model is presented as a mathematical programming model as the first step, and then, different parts of the mathematical model and their reflections in the real-world problem are discussed. The solution search method and the steps taken to implement it on the solution space of the mathematical model will be discussed in the next section. The following notations are used in this mathematical model:

| | |
|---|---|
| $i, i'$ | Set of all section lengths |
| $j$ | Set of all billets |
| $k$ | Set of all panel types (thicknesses) |
| $L$ | Billet length |
| $H$ | Billet height |
| $M$ | A sufficiently big constant |
| $N$ | A very small constant |
| $Lo_i$ | Lower bound of section i's length |
| $Up_i$ | Upper bound of section i's length |
| $FL$ | Total length of the floor plan |
| $B_{j,k}$ | $\begin{cases} 1 & \text{If billet j belongs to the type k} \\ 0 & \text{Otherwise} \end{cases}$ |
| $D_{i,k}$ | Integer parameter, the number of demanded panels with a length $S_i$ and type k |
| $S_i$ | Positive real variable; length of section i |
| $X_j$ | $\begin{cases} 1 & \text{If billet j is going to be used} \\ 0 & \text{Otherwise} \end{cases}$ |
| $w_j$ | The length of waste material on billet j |
| $a_{i,j,k}$ | Integer variable; the number of walls with a length $S_i$ of type k being cut from billet j |
| $NP$ | The number of different panel lengths used |
| $P_k$ | Price of a square meter of billet type k |
| $SC$ | Setup costs imposed by each new panel length |
| $Z$ | Objective function |

The solutions space of the problem will be defined with the following constraints:

$$\sum_j a_{i,j,k} \geq D_{i,k} \qquad \forall i,k \tag{4.7}$$

$$\sum_i a_{i,j,k} \leq M \times B_{j,k} \qquad \forall j,k \tag{4.8}$$

$$\sum_i \sum_k a_{i,j,k} \times S_i + w_j = L \times X_j \qquad \forall j \tag{4.9}$$

$$Lo_i \leq S_i \leq Up_i \qquad \forall i \tag{4.10}$$

$$\sum_i S_i = FL \tag{4.11}$$

$$NP = \frac{1}{2} \times \sum_i \sum_{i' \neq i} \frac{S_i - S_{i'}}{S_i - S_{i'} + N} \tag{4.12}$$

Furthermore, the objective function of the optimisation problem, which is going to be minimised, will be as follows:

$$Z = Min \sum_j \sum_k w_j \times P_k \times B_{j,k} \times H + NP \times SC \tag{4.13}$$

The objective function (Eq. 4.13) covers two objectives, and both converted to a capital nature to make them comparable. The first term adds up wasted panel lengths for each billet type and, based on the waste length and height of the billet, calculates the lost capital for each solution. The second term accounts for the component standardisation factor; it adds an extra cost to the objective function for each different wall length in the solution. The optimisation will therefore find a balanced number of billets, section lengths and cut lengths on different billets incurring the minimum cost. This objective function is in line with the concept of DfMA [168] which provides useful guidelines for optimising designs in terms of production and integrating processes in the product design. The DfMA guidelines relatable to building components include [25, 169]: (1) Standardise parts, (2) Minimise the number of parts, (3) Minimise material waste, (4) Minimise material types.

Eq. 4.7 forces the total number of wall panels cut from billets of all types to be greater than or equal to the initial demand. A wall panel will be cut out of a billet if and only if the wall type is similar to that of the billet, according to Eq. 4.8. Eq. 4.9 implies that for each billet used, the summation of all cut lengths and the waste is equal to the billet's length. Eq. 4.10 restricts the length of each section to a lower bound and upper bound, which are dictated by the architect based on architectural layout design considerations. Eq. 4.11 suggests that the summation of all section lengths is equal to the total length of the floor plan. Finally, Eq. 4.12 counts the number of different cut lengths in the panel-cutting plan, which is equal to the number of times that the lengths of each pair of panels are not equal. A very small number is added to the denominator, which prevents it from being equal to zero and making the whole fraction undefined, and the entire summation must be divided by two since each pair of panels are compared twice in the equation.

As seen in the mathematical model, the problem has a non-linear nature, and the solution space is much more complex than that of the CSP and BPP, which are NP-hard themselves. To handle this complexity, this study uses a GA, which is introduced in the next section.

## 4.7 Solution search method

GAs are search heuristics inspired by the genetic evolution of living organisms through natural selection and reproduction of the fittest offspring for the next generations. They try to imitate the steps that a population of species genetically undertake to evolve towards the fittest population. Similar to real-world, the algorithm first generates a random population and evaluates this population, then uses an iterative process to improve this population further until they reach a global optimum.

GAs have been used for structural [36, 156] and architectural [41, 167] layout optimisation method in the literature. To use the GA as the solution search method for the structural wall design problem, the variables of the real-world problem must be in the form of encoded chromosomes, made out of some genes. Therefore, the problem representation will look different from the one presented in the previous chapter, needing its own set of notations, as shown below. The entire solution search process utilised in this research is shown in Fig. 4.7. Each of the processes mentioned in this figure is discussed in detail in the remainder of this section.

- **Notations:**

| | |
|---|---|
| $N_p$ | The total number of population in each generation |
| $N_c$ | The number of crossover population |
| $N_m$ | The number of mutation population |
| $P_c$ | Crossover percentage |
| $P_m$ | Mutation percentage |
| $x_i$ | Demand vector for panels of type k |
| $d_k$ | The total number of panels of type k |
| $N_k$ | Permutation vector for type k panels |
| $Perm_k$ | Permutation vector for type k panels |
| $C_{j,k}$ | Vector of cuts on billet j of type k |
| $B_k$ | The number of type k billets used |
| $W_k$ | The total waste of material type k |

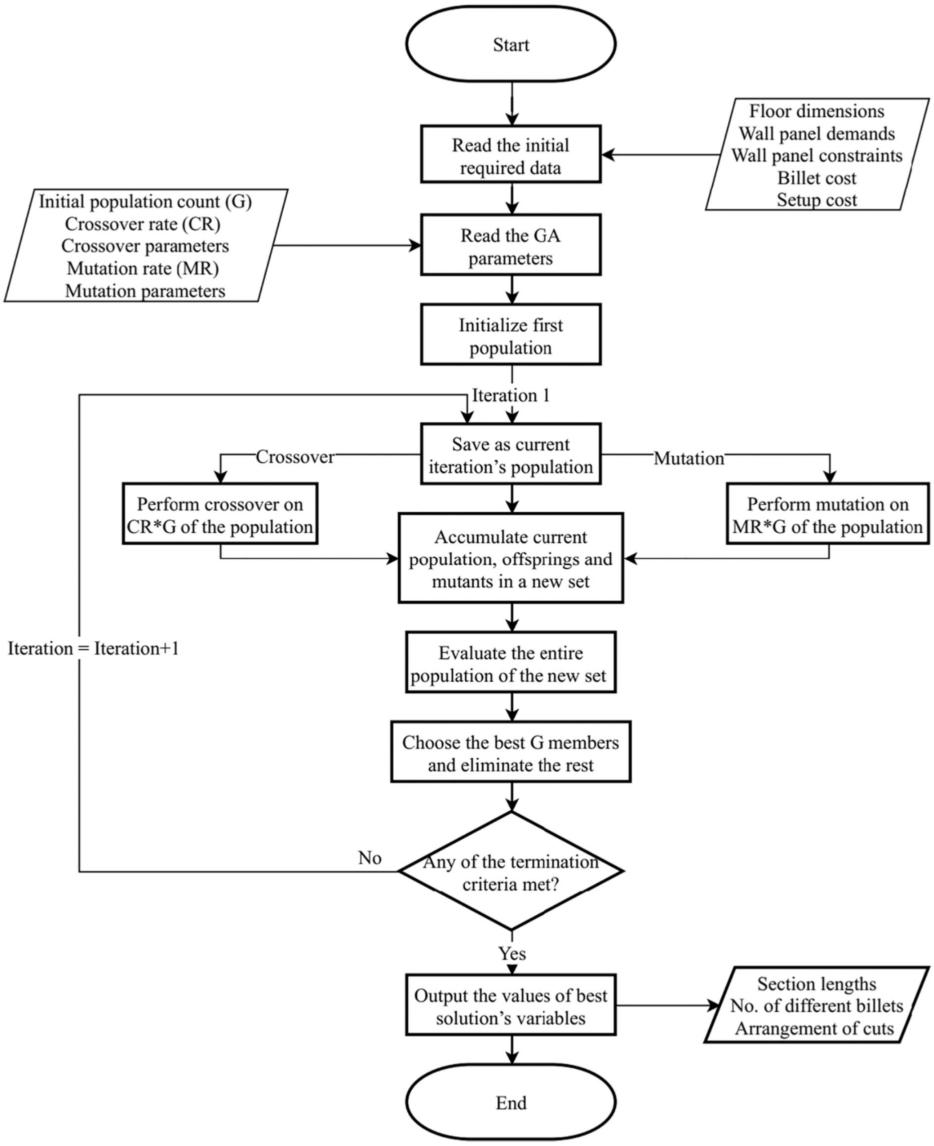



Figure 4.7: Optimisation process employed by the GA

### 4.7.1 Generating the initial population

Based on the mathematical model presented in the previous section, the main decision variables of this problem include: (1) Section lengths, (2) Arrangement of cuts across different billets, and (3) Total wasted length on each billet type. Each member of the initial population is, therefore, assigned two variables: a set of lengths for each section and a permutation variable. Therefore, each solution, also called chromosome in GA terminology, is assigned a set of strings, as shown in Fig. 4.8.

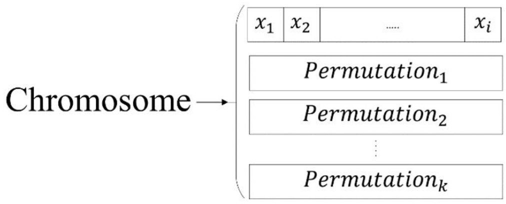



Figure 4.8: General representation of each solution

In the following subsections, the process of generating random values for each of these variables and how affecting constraints are taken into account have been discussed.

**Section lengths**

Section lengths are constrained by their lower and upper bound, and their total value is constrained to be equal to the floor plan's length. The generation process for this variable starts from generating $|i|$ uniform random numbers in the [0,1] interval; we call these numbers $x_i$. Each of these numbers will go through a parsing process, mapping them to lengths in the intervals given by the architect. The resulting lengths will have a one decimal precision, making them feasible for real-world application.

**The cutting plan**

For the purpose of the GA, the problem is modelled as a BPP, since the amount of waste produced is directly dependent on the number of billets used. The total amount of waste is minimised only if the total number of billets is minimum. Therefore, the problem is presented as finding the best permutations of a specific number of wall panels on a number of billets, that result in the minimum number of required billets. For this purpose, the input parameter of the demand will be generated based on the section lengths and the number of each panel type in each section. The input parameters of the current BPP must be extracted from the aforementioned parameters $D_{i,k}$ and $|i|$, to be used together with the section length variable $S_i$. The BPP must be solved separately for each material type; therefore, the demand matrix $d_k$ and the number of cuts $N_k$ for each k will be constructed in the below form:

$$d_k = [\overbrace{S_1 S_1 ... S_1}^{D_{1,k}} \overbrace{S_2 S_2 ... S_2}^{D_{2,k}} ... \overbrace{S_i S_i ... S_i}^{D_{i,k}}] \tag{4.14}$$

$$N_k = |d_k| \tag{4.15}$$

To generate an initial random solution to the BPP, first, each of the lengths is assigned a number based on their order in the $d_k$ matrix. Based on the $N_k$ which denotes the number of panels in the cutting plan of the material type k, there can be $N_{k-1}$ potential separation points in every permutation of the members of $d_k$. These points represent the separation point between every two billets. An example of a randomly generated solution with ten panel cuts is shown below:

$$\text{Input matrix}: [\overbrace{P_1 P_1 P_1 P_1 P_1 P_2 P_2 P_2 P_3 P_3}^{\text{Panel length}} \; \overbrace{000000000}^{\text{Separation points}} \; ] \tag{4.16}$$

$$\text{Permutation vector}(Perm_k): [18\ 19\ 12\ 3\ 15\ 14\ 9\ 1\ 4\ 6\ 7\ 10\ 2\ 16\ 8\ 11\ 17\ 5\ 13] \tag{4.17}$$

$$\text{Panel cut plan}: [\ 0\ 0\ 0\ \overbrace{P_1}^{\text{Billet1}}\ 0\ 0\ \overbrace{P_3 P_1 P_1 P_2 P_2}^{\text{Billet2}}\ 0\ \overbrace{P_2 P_3 P_1}^{\text{Billet3}}\ 0\ 0\ \overbrace{P_1}^{\text{Billet4}}\ 0\ ] \tag{4.18}$$

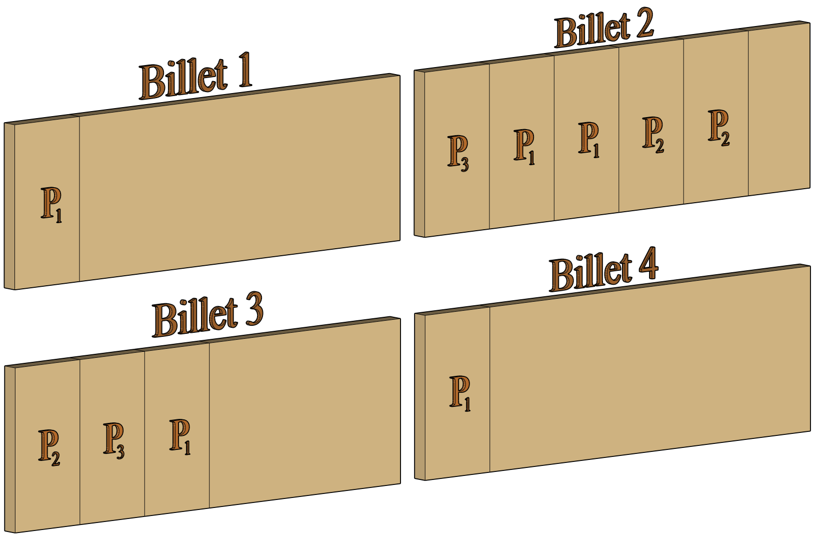



Figure 4.9: Illustration of the example permutation

The number of billets corresponding to each random permutation, as shown above, will be termed $BI_k$ from now on. As seen in the example, the randomness of the permutation can make the solutions infeasible, which will be controlled using a penalty function, explained thoroughly in the solution evaluation section. The outputs extracted from the solution are the number of billets ($BI_k$) and the matrix of cuts on billet j of type k ($C_{j,k}$), which is equal to the first term in Eq. 4.9 of the mathematical representation.

**The waste**

The total waste, as mentioned before, depends on the number of billets used for each material type. The amount of waste for each material type is equal to the difference between the total length of the billets used and the demand. The notation used for this variable is $W_k$ and is calculated as follows:

$$W_k = B_k \times L - \sum d_k \tag{4.19}$$

### 4.7.2 Solution evaluation

The population of the solutions will need to be evaluated on each iteration of the GA. To evaluate each solution corresponding to each member of the population, the objective function must be established again based on the new format of the model. The objective function here must include the total amount of waste for each billet type, as well as the penalty associated with the cut length violation (Eq. 4.9). The objective function is introduced as follows:

$$Cost = \sum_{k} W_k \times P_k \times H + NP \times SC + \alpha \times \sum_{k} V_k \tag{4.20}$$

The first and second terms are similar to the mathematical representation of the problem, denoting costs associated with each new panel's waste and setup cost. The third term ($\alpha \times \sum_k V_k$) is the penalty, consisting of a multiplier ($\alpha$), which implies the weight of the penalty term against other terms in the function, and a violation ($V_k$). These terms are calculated as follows:

$$V_k = N_k \times \frac{1}{BI_k} \times \sum_{j} \frac{CLj,k - L}{L} \tag{4.21}$$

In Eq. 4.21, $V_k$ is the mean violation for each panel type multiplied by the total number of cuts required of that type. After the initial population has been evaluated, the algorithm chooses the best members of the population proceeds to genetic operators where these solutions are utilised to produce the next iteration's population.

### 4.7.3 Genetic operators

Generally, there are three types of operators in GAs; selection, crossover, and mutation. Selection prioritises the better members of the population when choosing them as members that will pass on their characteristics to the next generation. The crossover combines the characteristics of two parents chosen by a selection method and produces child solutions out of them. Finally, the mutation operator randomly changes the characteristics of a proportion of the population and produces children for the next population to avoid convergence to a local minimum.

#### Selection

The current GA selects the members of each population based on the "roulette wheel" selection method. This method uses a probability function to calculate the likelihood of being chosen for each member of the population based on the fitness of the member. The selection probability for each member of the population ($n \in N$) is calculated based on the Boltzmann selection method [170].

#### Crossover

The selection method used for this crossover process is the aforementioned roulette wheel's method. Each member of the population, as discussed before, is assigned two different variables. The section length variable is a real random number generated in the [0,1] interval, and the cutting plan variable is in the form of a permutation vector. The crossover operator has to be applied to these variables with different approaches. The algorithm will apply the crossover between either the section length variable or the permutation variable, or both, with equal probabilities.

*Arithmetic crossover:* The procedure of applying a crossover operator on real values is performed based on the "whole arithmetic crossover" method [171]. When two members of the population are going through this operation, their corresponding real variables are changed according to the below process.

*Permutation crossover:* In the case of the permutation variable, which is in a vector form and the order of the arrays is important, the operator first chooses the crossover section. Arrays of the vector that are after the section's location will be swapped between the two vectors. In the case of likely infeasibilities induced due to this operator, simple operations will return the solution to the feasible solution area. As shown in Fig. 4.10, the crossover section dictates that three of the arrays must be swapped, which induces a duplication in the child strings. The child string is then fixed by replacing the duplicate cell in the non-mutated part, as shown by the red colour.

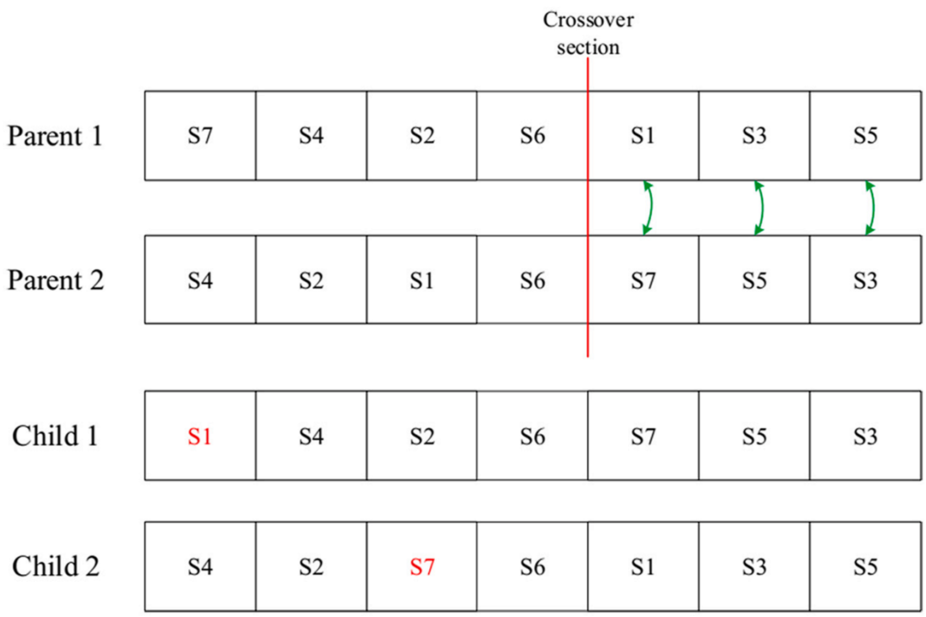



Figure 4.10: Example of the permutation crossovers

**Mutation**

For each member of the population, the mutation can be performed on either the section lengths or the permutation vector, or both. The choice on the variable to mutate is made randomly with equal probabilities. Two different types of mutations have been used in this research, based on the type of the variable. A Gaussian mutation [157] has been used for the length variables, shown as the first string in Fig. 4.8. For the rest of the strings in this figure, a permutation mutation has been employed as discussed below.

*Permutation mutation:* Three different operators have been used in this model to mutate the permutation variable for each member of the population. Each member chosen to be mutated on their permutation variable will go through one of these operators, shown in Fig. 4.11. As seen in this figure, each of these operators requires a random selection of two arrays of the vector.

- *Swapping:* Takes two arrays of the vector and swaps them with each other.
- *Reversion:* Takes two arrays of the vector and reverses the order of appearance in the string between them.
- *Insertion:* Takes two arrays of the vector, randomly removes one of them, and inserts it in front of the other.

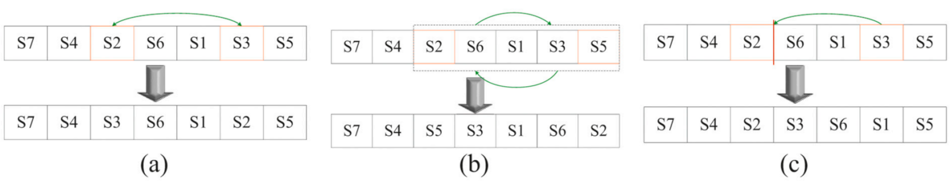



Figure 4.11: Mutation operators: (a) Swapping, (b) Reversion, and (c) Insertion

### 4.7.4 New generation selection

After performing all genetic operations, the algorithm must proceed to subsequent iterations, which requires selecting a new population to repeat all of the above operations. The population of the new generation will be equal to the initial population (G), and the members will be chosen through the following steps:

1. The previous population, offspring, and mutants are gathered in a new set.

2. The resulting set is arranged in ascending order, based on their objective function value.

3. The first G members of the set are kept, and the rest are eliminated. The resulting set will move on to the next iteration as the new generation.

## 4.8 Case study

To illustrate the validity of the model and the solution search algorithm presented in this research, they are applied to a case example in this chapter. The example case is a hypothetical rectangular floor plan with a 26m length dimension. The designer requests a wall-length design that is made up of five sections (wall groups), while each section has characteristics shown in Table 4.1. The layout of the hypothetical floor plan is shown in Fig. 4.12. “The input parameters of the hypothetical case example have been presented in Table 4.2 and Table 4.3.”

There are three different panel types, and the number of demanded wall panels of each type is also shown in Table 4.1. The billet length for all panel types is equal to 16m. The costs associated with each solution are also shown in Table 4.2.

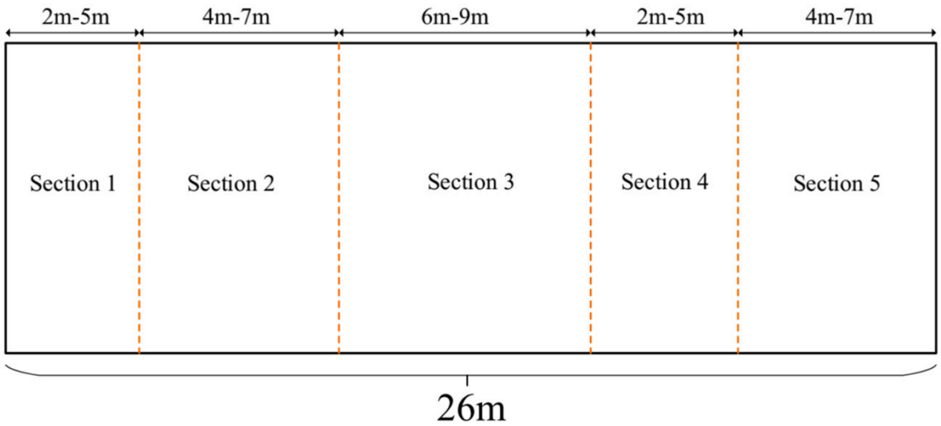



Figure 4.12: Illustration of the hypothetical case example

Table 4.1: Length constraint and demands of each floor plan section

| | **Section 1** | **Section 2** | **Section 3** | **Section 4** | **SSection 5** |
|---|---|---|---|---|---|
| Length Interval | [2,5] | [4,7] | [6,9] | [2,5] | [4,7] |
| Type 1 demand | 0 | 10 | 2 | 5 | 10 |
| Type 2 demand | 4 | 2 | 3 | 8 | 2 |
| Type 3 demand | 1 | 6 | 9 | 1 | 0 |

Table 4.2: Material Costs

| **Item** | **Cost** |
|---|---|
| Type 1 ($\$/m$) | 1 |
| Type 2 ($\$/m$) | 1.5 |
| Type 3 ($\$/m$) | 1.8 |
| Machine setup ($/different length) | 10 |

The aforementioned data are entered into the GA in conjunction with

Table 4.3: GA parameters

| Parameter | Value |
|---|---|
| Population | 400 |
| Selection pressure | 5 |
| Crossover percentage | 40% |
| Mutation percentage | 80% |

the GA parameters shown in Table 4.3. The GA has been coded in the MATLAB software (R2020a), and the algorithm's convergence was tested by setting a large number of iterations as the algorithm's termination criterion. The next section presents the results and a discussion around the findings of this research.

## 4.9 Results and discussion

The GA code was run ten times and for 10,000 iterations, and the results were reported as shown in Table 4.4. The algorithm has converged to different optimums in the given number of iterations every time. This global optimum was found three out of ten times the algorithm was run within an acceptable amount of time.

Table 4.4: Results of the optimisation run instances

| # Run | Best cost | Iterations | Time (s) | # Run | Best cost | Iterations | Time (s) |
|---|---|---|---|---|---|---|---|
| 1 | 58 | 75 | 16 | 6 | 44.54 | 177 | 37 |
| 2 | 55.62 | 348 | 81 | 7 | 54.07 | 3796 | 788 |
| 3 | 54.07 | 404 | 80 | 8 | 52.49 | 2754 | 577 |
| 4 | 44.54 | 6808 | 1395 | 9 | 44.54 | 235 | 50 |
| 5 | 55.68 | 372 | 80 | 10 | 48.94 | 2555 | 570 |

As seen in Table 4.4 the convergence of the algorithm is not satisfactory, which is a result seen in other literature as well [167]. Stochastic outcomes are common in GA experiments, and a fair comparison reports a number of experiments and not only the best results [157]. Also, in the complex solution space of spatial optimisation problems, finding a set of well-performing solutions, and not necessarily the global optimum, is common. The generative design algorithms are usually run for a number of instances to generate several solutions, of which one is a near-optimum solution. Details of the near-optimal solution are reported in Table 4.5 and Table 4.6 and Fig. 4.13. Table 4.5 shows the optimum number of billets and section lengths in the optimal design configuration, and Table 4.6 reports the arrangement of different cuts on the billets, and, Fig. 4.13 shows the panel production plan in the form of panel cuts on the billets.

Table 4.5: Optimisation results; section lengths and billets

| Section No. | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Lengths | 3.7 | 5.3 | 8 | 3.7 | 5.3 |
| Billet type | 1 | | 2 | | 3 |
| No. required | 9 | | 6 | | 7 |

Table 4.6: Cutting plan of the example problem

| Type | No. | Cut lengths | | | Waste | Type | No. | Cut lengths | | | | Waste |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 5.3 | 5.3 | 3.7 | 1.7 | 2 | 3 | 3.7 | 3.7 | 3.7 | 3.7 | 1.2 |
| 1 | 2 | 5.3 | 5.3 | 5.3 | 0.1 | 2 | 4 | 3.7 | 3.7 | 3.7 | 3.7 | 1.2 |
| 1 | 3 | 8 | 3.7 | 3.7 | 0.6 | 2 | 5 | 8 | 3.7 | 3.7 | - | 0.6 |
| 1 | 4 | 5.3 | 5.3 | 5.3 | 0.1 | 2 | 6 | 8 | 3.7 | 3.7 | - | 0.6 |
| 1 | 5 | 5.3 | 5.3 | 5.3 | 0.1 | Waste on #2 | | 6.4 | | | | |
| 1 | 6 | 5.3 | 5.3 | 5.3 | 0.1 | 3 | 1 | 5.3 | 5.3 | 5.3 | - | 0.1 |
| 1 | 7 | 5.3 | 5.3 | 5.3 | 0.1 | 3 | 2 | 5.3 | 5.3 | 5.3 | - | 0.1 |
| 1 | 8 | 8 | 3.7 | 3.7 | 0.6 | 3 | 3 | 8 | 8 | - | - | 0 |
| 1 | 9 | 5.3 | 5.3 | 5.3 | 0.1 | 3 | 4 | 8 | 8 | - | - | 0 |
| Waste on #1 | | 3.5 | | | | 3 | 5 | 8 | 3.7 | 3.7 | - | 0.6 |
| 2 | 1 | 8 | 5.3 | - | 2.7 | 3 | 6 | 8 | 8 | - | - | 0 |
| 2 | 2 | 5.3 | 5.3 | 5.3 | 0.1 | 3 | 7 | 8 | 8 | - | - | 0 |
| | | | | | | Waste on #3 | | 0.8 | | | | |

As seen in Table 4.6, the amount of waste on each billet is so small, not exceeding the minimum cut length, which shows the efficiency of the waste minimisation function. The algorithm has also tried to minimise the variety of cuts by choosing three different lengths. In the literature, different amounts of waste have been reported by the industry reports for the CLT cuts in the CNC milling plants, ranging from 15% to 27% [172, 173]. These amounts include the total waste on all panel types, including structural and non-structural elements. Since the designer tries to minimise the number of openings in the structural elements, non-structural elements will be responsible for a large amount of waste due to openings. Therefore, to make a non-biased comparison, we assume the worst case, which forces door openings on more than half of the structural elements in the above case example. It is assumed that each door has a one-meter width and a height equal to the wall panel. The price of the waste on each billet is calculated based on the amounts given in Table 4.5. As seen in Eqs. 4.22 to 4.25, the amount of material waste in the worst case is limited to 6.38%, which is significantly lower than the amounts reported in the literature (15%-27%) and shows the optimality of the waste minimisation algorithm. This improvement, accompanied by an increase in the standardisation compared to fully custom designs, shows the potential of improving MC factors at the early stages of design.

$$\text{Total price} = 16 \times [9 \times 1 + 6 \times 1.5 + 7 \times 1.8] = 489.6 \tag{4.22}$$

$$\text{End cut wastes} = 3.5 \times 1 + 6.4 \times 1.5 + 0.8 \times 1.8 = 14.54 \tag{4.23}$$

$$\text{Opening wastes} = 5 \times 1 \times 1 + 3 \times 1 \times 1.5 + 4 \times 1 \times 1.8 = 16.7 \tag{4.24}$$

$$\text{Total waste percentage} = (14.54 + 16.7)/489.6 = 6.38\% \tag{4.25}$$

Limitations of the research include its inability to reflect some special cases of design, for instance, where a beam element is used on top of the openings, and therefore, the wall will consist of two cuts on both sides of the opening. The model also does not apply to simply supported spans, where wall elements can appear in both directions of the building floor plan. Further, the model has been tested on a hypothetical case with a rectangular floor layout for simplicity.

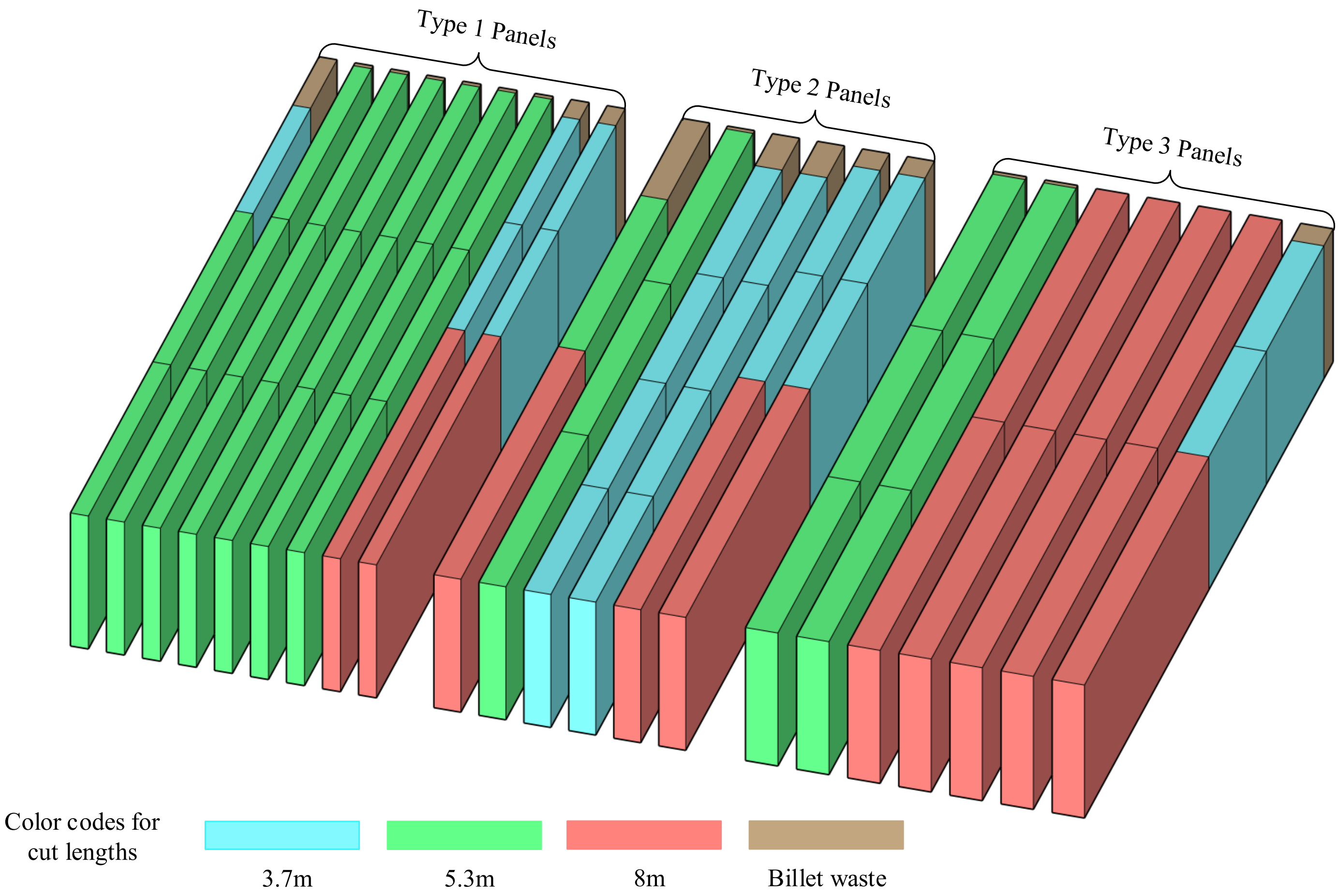



Figure 4.13: Example case's solution

## 4.10 Conclusions

This chapter presented a mathematical model aiming at integrating production process variables into the CLT building's preliminary design stage. The model used a mathematical framework to optimise the layout of structural walls using a novel GA technique. It considered both the product waste, i.e. material waste in the CNC machining plant and process waste, i.e. the level of standardisation in the production processes. This contributes to the MC of buildings by significantly increasing the MP efficiency while maintaining a high level of customisability, close to the traditional design-to-order context, in the final product. It can also lead to demand certainty, which will support suppliers in maintaining a continuous production line.

The model assigned varying lengths to different wall categories that form the final load-bearing components covering the entire building footprint while increasing the level of standardisation in the panel lengths. Simultaneously, it searched for the best permutation of the resulting panels on the billets which had the minimum material waste. The proposed framework minimised the material waste to less than half of the amounts commonly reported in practice. Also, the production process was optimised by objectively decreasing the panel variety from five to three different lengths. This led to an increased similarity in production and assembly operations, based on the DfMA guidelines.

In practice, this model can be used by the designer to generate structural wall layouts that are less wasteful in terms of billet usage and more standard in terms of shape. In the case of some panel manufacturers who offer a cheaper set of made-to-stock standard panel sizes, the flexible structure of the model allows for adaptation to the new problem conditions. Further, this model allows the architect to trial diverse preferences of the structural walls and in order to obtain an early estimation of the production wastes before finalising design revisions.

The developed framework is a design support tool that integrates SC processes into the design phase with a view to increasing the mass-customisability of the final building product. In the context of the housebuilding industry, where scattered and temporary SCs are prevalent, the existence of such tools is advantageous. It is specifically beneficial since it considers the production variables and suppliers limitations without reliance on direct engagement with the suppliers. This tool is utilisable at the early stage of design without compromising the flexibility and customisability of the architectural layouts.

The current model does not aim to function as a design platform. Nonetheless, its integration with existing design platforms can make real-time design suggestions to the architects and potentially increase its ease of use and applicability. In order for such an integration to perform seamlessly, further research is required. Another limitation of the research is its applicability to a specific structural system (i.e., CLT), which should be further generalised to verify its applicability to a wider range of building systems. Also, further research is required to assess the versatility of the model for non-rectilinear building layouts or layouts with bidirectional structural wall systems. Other potential areas for future research include expanding the model for other prefabricated building systems, accommodating more design details in the current model to reflect other real-world design scenarios, improving the model by adding a wider range of variables from transportation and assembly operations.

# Chapter 5

# A Practical Framework for Automated Design of CLT Buildings for Mass-Customisability in a Digital Environment

## 5.1 Overview

CLT is a green structural system that promotes the prefabrication of multi-storey buildings. DfMA has proven effective in enabling its efficient factory production and onsite installation. However, little has been done to embed DfMA principles in the design of such systems systematically. This chapter, therefore, introduces an automated design framework for enacting DfMA principles in multi-storey CLT buildings. It focuses on the geometry of load-bearing CLT walls as the architectural and engineering design meeting point. It uses a novel Greedy-Genetic Algorithm (G-GA) to find the optimal DfMA-enabled structural wall design on a BIM platform. The generated outputs assist designers in choosing an optimal design alternative for efficient production and also aid the suppliers in making early arrangements regarding their processes. The model was implemented on an eight-storey building and successfully minimised both material and process wastes. This chapter aims at making the design optimisation algorithm presented in the previous chapter further operational and harnessing the power of BIM tools to make such algorithm further flexible in information transfer along the SC.

## 5.2 Introduction

The low productivity of the construction industry is predominantly attributed to inefficient onsite processes. As a response to this issue, the industry has recently adopted industrialised construction methods by shifting onsite operations to offsite fabrication [174]. Offsite fabrication of building components in the controlled factory environment has a significant potential to improve the overall productivity across the building SC.

Moving larger amounts of the building production processes to the factory environment leads to higher standardisation of the final product and thus can increase the overall efficiency. However, a highly standardised building may lack customisation and is not usually well perceived by the end-users and can result in revenue loss for the construction company [122]. A solution is to find an optimal prefabrication level that exploits the benefits of industrial production while maintaining a level of customisation acceptable to the customer.

To provide customers with the element of choice, the building design must offer flexibility in certain aspects that are valuable to the customers. An approach for implementing prefabrication in this custom built-oriented context is building productisation which means breaking the building into its sub-products [24]. In doing so, high levels of standardisation and prefabrication can be applied to sub-products that have intangible value in offering choices to the customers [27]. The building structure may be an example sub-product that has a high potential for prefabrication since it can be standardised in such a way that it still enables customisation of architectural spaces [27]. Nonetheless, this is not an easy task since living spaces are not usually independent from the structure. Deciding on the structural design specifications to maximise standardisation while not interfering with the required architectural freedom is a multifaceted design challenge that can be subject to optimisation.

CLT is a green structural building system that lends itself to prefabrication. CLT buildings employ planar modules as load-bearing elements. This building system offers high efficiency for onsite operations [30, 175, 176], making it economically viable despite its relatively higher supply cost. In contrast to volumetric modular systems, CLT systems are panelised and hence, offer a high level of architectural versatility [177] as they do not standardise living spaces.

In practice, the process of designing a CLT building begins with the preliminary design stage, in which architectural spaces are determined, and an initial positioning and sizing are performed for the structural CLT members [161, 178]. The preliminary design commonly produces the governing layout drawings for the entire design stage, resulting in the final shop drawings and component details used at the production stage. The preliminary design, however, tends to overlook production variables and how design details can affect the efficiency of manufacturing and assembly operations. This issue is the main motivation for this research as it frequently causes inefficiency in CLT projects. To tackle this issue, construction has adopted the concept of DfMA from the manufacturing industry [179]. DfMA encourages considering the ease of fabrication and assembly by following qualitative design guidelines as well as quantitative evaluation of design [180]. Most recent developments suggest using a combination of both qualitative and quantitative approaches through a fully automated design process [181].

Automated design methods provide a means to explore a large number of design alternatives in search of the optimum design in a quantitative evaluation process [41, 40]. BIM platforms enable interactive visualisation and inter-disciplinary data exchange in a systematic design process among different SC participants [182, 32]. BIM technology provides rich outputs such as drawings and visual details, process information, and bills of quantities. However, in an automated design process where design exploration algorithms are needed to find optimal design values, the conventional capabilities of BIM software are limited. Therefore, low-level programming languages need to be utilised for computations, which need to communicate with BIM software through their API.

In summary, a comprehensive framework for utilising BIM platforms for DfMA-oriented structural design optimisation of buildings in an automated and visual fashion is non-existent in the literature. Such a framework must address various aspects of the design automation process by incorporating design variables and objectives, an optimisation algorithm, and a mechanism for converting the algorithm's outputs into the BIM environment. Hence, the objective of this research is to propose an automated BIM-based design support framework that aims at optimising the structural layout of CLT buildings based on DfMA guidelines. The proposed framework uses a hybridised G-GA to find an optimal building layout for manufacture and assembly. A visual model of the structural system is then generated in a BIM platform, which can be used to generate other process information, including shop drawings and assembly schedules. This model is able to automatically produce bills of materials and provide an early cost estimate based on the volume and weight of the CLT components.

## 5.3 Literature review

This section will discuss the literature in different areas pertaining to the objective of this research to provide a basis for developing the design support framework and answer the following research questions.

- Which DfMA approach best suits an automated design tool for the CLT?
- What variables better reflect DfMA goals in the design?
- What modelling method is the best for defining these variables?
- What type of algorithms (exact/heuristics/meta-heuristics) is the best for

this purpose?

### 5.3.1 Design for Manufacture and Assembly

As its name implies, the emphasis of DfMA is on enabling optimal efficiency in manufacturing and assembly operations by introducing new principles and ways to the design work [181, 168]. There is a general consensus that DfMA can be effectively implemented if the process begins at the early design stages [180, 169]. This process can be implemented using three different approaches: (i) following a set of general rules or guidelines, (ii) quantitative design evaluation, and (iii) automating the entire process [181]. The latter is the most recent trend and uses a hybrid of the other two approaches as the basis for an iterative optimisation system.

With its capabilities in capturing and transferring digital data, BIM can greatly contribute to implementing DfMA [20]. In response to the DfMA requirements, BIM provides a platform for parametric design by accounting for efficiency factors across the entire construction SC [183]. In line with this, previous studies have confirmed the value of BIM tools for increasing efficiency in offsite construction methods [180, 184, 185]. As suggested by Bogue [181], if the parametric nature of the BIM design software can be combined with the flexibility and optimality offered by algorithmic design methods, BIM can become a powerful means for automating the design process. Nonetheless, the literature is slim in detailing how to achieve automation and optimality in BIM-enabled DfMA processes [186].

The slow adoption of the DfMA concepts in construction can be partly attributed to the differences between the manufacturing and construction sectors [180, 169]. Construction scholars have placed more emphasis on addressing this issue in recent years. Systematic literature reviews such as [180, 186] or critical comparative studies such as [187] are examples of such endeavours toward successfully adopting DfMA for the construction industry. In addition, conceptual frameworks for implementing the DfMA in construction have been developed to improve automation in the building design processes [183, 188]. Despite their valuable findings, such scholarly works are limited and predominantly intuitive or scenario-based; thus, their proposed solutions tend to be sub-optimal.

Automating the design process requires an iterative design approach in which different design alternatives are evaluated and refined multiple times until an optimal design solution is reached [178, 154]. This relies on developing algorithmic design systems that can efficiently create a large set of feasible design solutions and automatically select the best design option [25].

### 5.3.2 Architectural and Structural Optimisation

Studies in the area of the automated design commonly involve the exploration of a large set of design alternatives to find optimal structural or architectural design variables [189, 190]. A number of studies have focused on improving building layout by considering the location, size, and geometry of building spaces and objects. The ultimate aim was to optimise different structural, architectural, and production systems [178]. Architectural layout optimisation methods majorly aim at improving building architectural aspects such as space utilisation [41], total distances among spaces [191], lighting and energy consumption [49, 150], and occupant satisfaction [192]. On the other hand, structural layout optimisation studies address structural objectives such as efficient load transfer, structural weight and eccentricity [154, 35, 36].

Scholars have applied different techniques to identify and refine design solutions for better performance in terms of structural and architectural objectives. Michalek et al. [41] used gradient-based algorithms and GAs to generate floor plans consisting of rectangular spaces. GAs have been widely used in other studies for the purpose of architectural layout generation [167, 193, 194, 195, 196, 197]. Mixed-Integer Programming (MIP) has also been used for the same purpose by Keatruangkamala and Sinapiromsaran [198]. Other methodologies in the literature include Integer Linear Programming (ILP) [191], Simulated Annealing (SA) [199, 200] and evolutionary algorithms [201].

It should be noted that evolutionary algorithms offer high computational capabilities for spatial optimisation problems, which is necessary due to the complexity of solution sets in such problems [189, 202, 203]. The aforementioned studies address both modelling and optimisation of the design values. However, more recently, Gan [204] introduced a graph-based technique established on a BIM platform to describe the essential physical characteristics of volumetric modular buildings. Although this research does not tackle the optimum finding in such buildings, its graph-based definition of the building provides a useful means for the generative design of volumetric buildings. The results of this research provide a realistic set of design alternatives that can be investigated to find the optimum solution.

In a structural layout context, GA has been utilised for the automated design of beam-slab layouts for rectangular [154] and rectilinear floor plans [36]. Boonstra et al. [42] used design response grammars and evolutionary algorithms to automatically design a structural system that fits into the given spatial design. Qiao et al. [205] used the Global Convergent Method of Moving

Asymptotes algorithm to find the best location of components and pseudo-densities in multi-component structures. Degertekin et al. [206] used the Jaya algorithm to optimise the size and layout of truss structures. Wang et al. [207] employed a multi-objective optimisation method to optimise layout design for multi-component structures for better structural stiffness and heat transfer.

The aforementioned studies provide two typical insights; a) they are useful in understanding the modelling process of the building layout, and b) their methodologies demonstrate different approaches to defining the search space for building objects and space positioning along with methods for finding the best solution. Nonetheless, they have two weaknesses; a) their intended objectives do not consider production variables b) their scope does not include MT as a new construction system. These are important to be addressed, particularly due to the industry's targets for less wasteful and greener construction methods.

### 5.3.3 Production Optimisation

A few studies aim to improve production operations, including manufacturing, transport and assembly. Liu et al. [208] presented an automated architectural layout generation tool considering architectural constraints besides manufacturing cost and constraints for pre-cast concrete structures. Since this model is developed for concrete structures, the modelling view toward the building components is additive (i.e. pre-cut concrete blocks are added to create walls) rather than subtractive (i.e., the desired components are cut from a large standard mother panel). However, this study disregards the wall thicknesses to reduce the mathematical model's computational complexity [208]. [209] presented an identification and selection method for concrete modular structures based on the optimality of module connections, transportation, lifting and total volume. Like the previous study, this model uses a rather additive approach and does not consider the ease of manufacturing or the material waste during the production stage.

### 5.3.4 Summary

Design work is an important means for streamlining the processes across the entire SC, especially in the case of construction, where communicative means are less feasible due to temporary and project-based supplier relations. The literature review established that evolutionary methods are useful when tackling design problems with a large number of alternatives. In addition, general design rules, such as DfMA guidelines, are specifically a proper solution for the construction's SC structure since they are general and not dependent on the suppliers' production processes.

Construction scholars have recently begun to design optimisation methods that broadly incorporate manufacturing, transportation and assembly stages for MT buildings [178, 210]. These are initial steps towards a fully parametric design optimisation platform for MT buildings. To take a step further, the goal of this study is to develop a digitised platform that enables optimal DfMA of MT buildings. Unlike the previous DfMA-based studies, the platform facilitates subtractive design which is necessary for waste minimisation when manufacturing building components. Moreover, the proposed platform integrates the optimisation model with BIM to achieve accuracy and automation in identifying optimal design solutions.

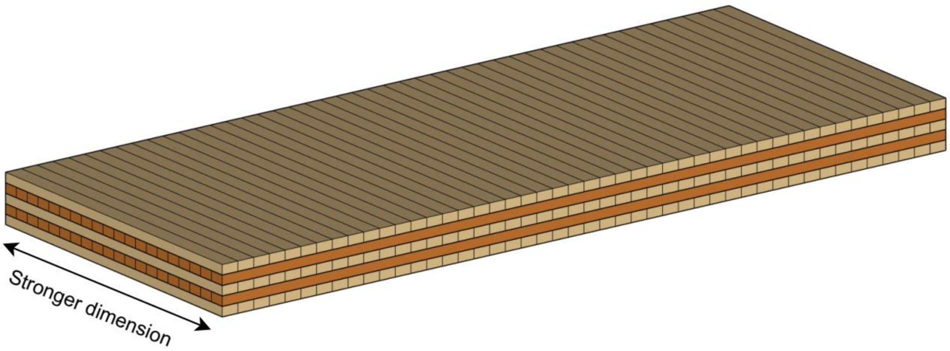
Therefore, a mathematical model is developed, and realised through a hybrid algorithm (G-GA) in the python programming language to find optimal CLT wall geometries in terms of DfMA objectives. The study specifically addresses the CLT wall panels, as they are structural members that affect building floor layout and, thus, a proper representative for the interactions between different specialties, i.e. architects and structural engineers, involved in the design process. In addition, their geometrical details affect their ease of manufacturing and material waste in the factory. The optimisation results are then transferred to Autodesk Revit software via Dynamo visual programming interface. The resulting Revit model is then utilised to obtain bills of materials and design details, which the suppliers can use for streamlining their processes.

## 5.4 Methodology

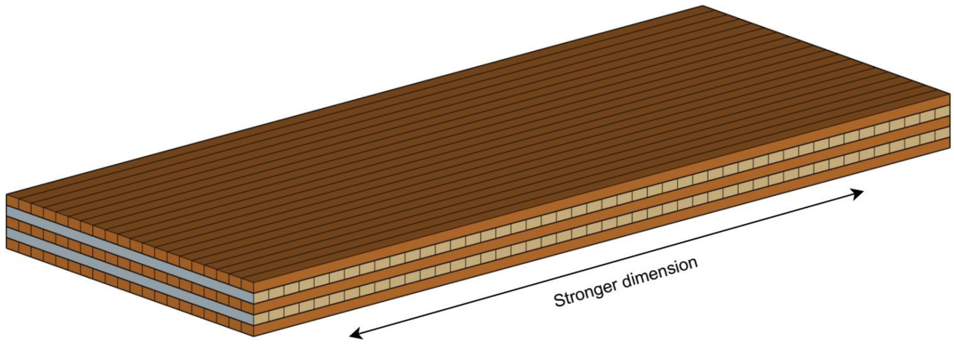
This section details the process of developing, programming and executing the proposed design support tool for DfMA-enabled CLT wall systems. It begins with a brief introduction to CLT buildings and how DfMA principles are implemented at their preliminary design stage. Then, it elaborates on the modelling process developed for the structural wall systems design. Further, it explains the optimisation method utilised for finding the optimal wall design that meets DfMA objectives. Finally, the section concludes by detailing the visualisation method on a BIM platform.

### 5.4.1 DfMA-Oriented Design of the CLT Structural Wall System

A CLT system uses timber panels for both horizontal and vertical load-bearing members, with structural characteristics similar to the pre-cast concrete building system [178]. CLT panels are made by gluing an odd number of timber layers, with each layer's grain direction perpendicular to its adjacent layers [211, 212, 213]. CLT is first made of large panels called billets, which are then cut to attain the desired dimensions for floor and wall members in the manufacturing plant. The stronger dimension of the billets used for floor panels is its longer dimension, while for the wall panels is its shorter dimension (Fig. 5.1), usually equal to the floor height of the building. This is helpful because it simplifies the structural modelling of walls, as discussed in the following section. As a result, CLT wall panels usually require cuts only in one dimension.




(a)




(b)

Figure 5.1: CLT billets used for (a) Structural walls (stronger in the shorter dimension), and (b) Floors (stronger in the longer dimension)

The preliminary design process of a panelised CLT structural systems starts with dividing the given floor plan into various architectural spaces and choosing the location of structural members (including both floor and wall members) [178, 162]. The preliminary design of structural walls is simplified using span tables provided by the manufacturers or national standards. This design approach is limited to a basic analysis of the vertical loads imposed on each wall, i.e. loads from upper-level walls and the upper floor supported by the wall. This approach avoids complex structural calculations since such calculations are not usually necessary at the early design stage, and they rarely affect the positioning and length of the structural members [161].

Therefore, the present research adopts this design approach to simplify structural design works and facilitate early engagement of CLT manufacturers. Yet, it satisfies fundamental structural requirements of the building codes for CLT buildings mainly by considering the structural members' positioning, thickness, and length. This is an inter-disciplinary design approach in which the architect determines a precise wall-to-wall dimension for each open space but allows a range for the other building dimension (i.e. wall length) to accommodate structural constraints. This complies with the apartment design guides for living spaces because such guides usually suggest a range of values for the area of different spaces, along with a range of acceptable aspect ratios (i.e., dimension1/dimension2) [214]. This range will be the acceptable range for the second dimension, equal to the CLT wall lengths in this study. Different variables and parameters of the current problem are shown in Fig. 5.2 on an example adopted from Woodard and Jones [162].

The developed model is generalisable and applicable to other one-way spanning systems by adjusting the values of input parameters, including:

1. DPs

    - The number of panels in the entire building
    - Type of each panel
    - Location of panels in the building plan drawings
    - interrelations among panel lengths due to their real-world positioning

- The length limits for each panel/group of panels specified by the architect to maintain architectural quality.

2. Manufacturer details

   - Size of the billets used by the manufacturer
   - Unit cost for each panel type
   - Unit weight for each panel type
   - Extra cost due to machine setup.

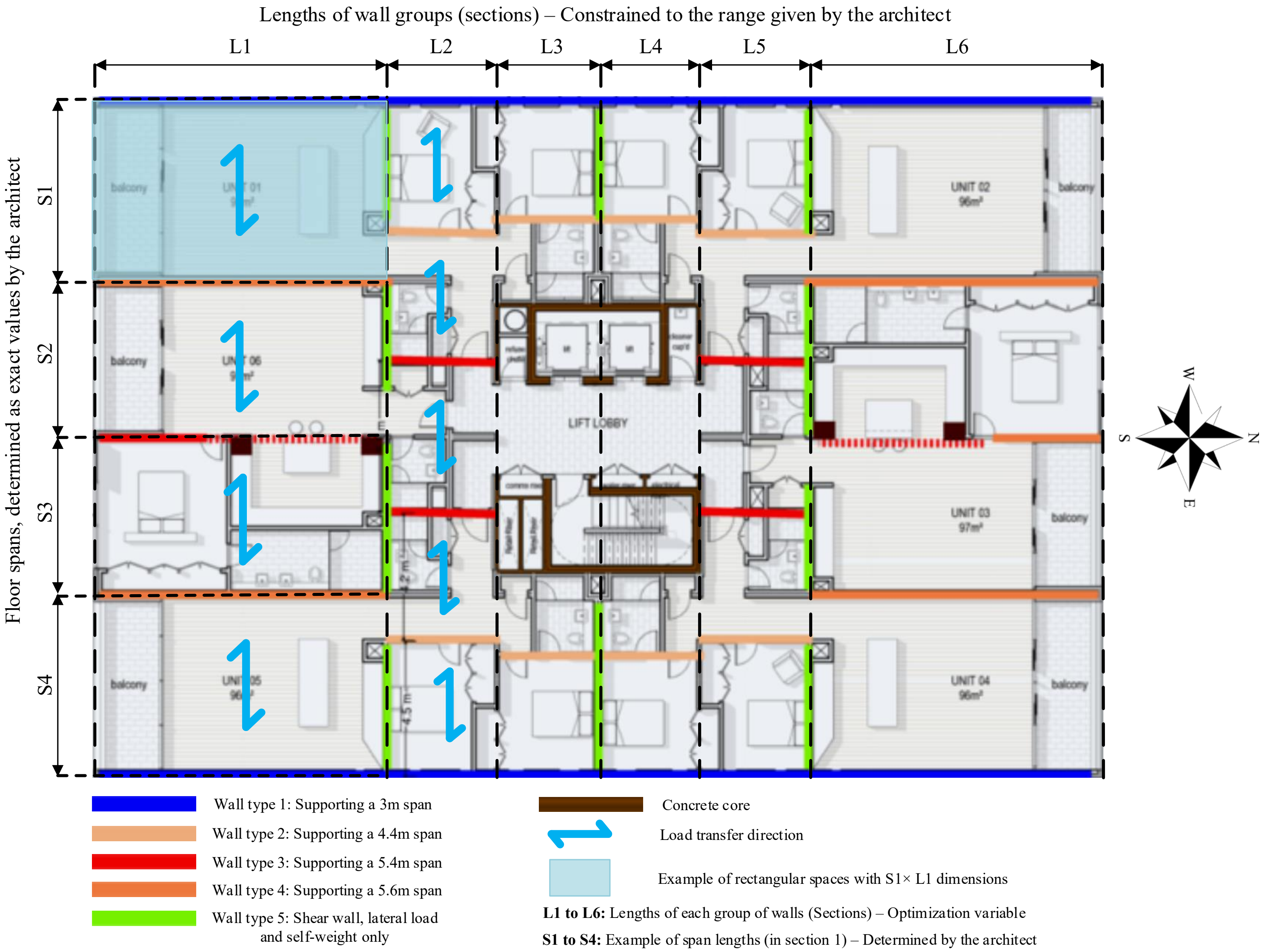



Figure 5.2: Example floor plan with a one-way spanning floor system (adopted from Woodard and Jones [162]

Flooring systems utilised for CLT structures are typically one-way spanning slabs, and this leads to walls being vertically load-bearing in one direction only (North/South walls in Fig. 5.2). As seen in Fig. 5.2, the load-bearing walls usually form groups regarding their length since they support the same floor panels (e.g., all walls in the L1 section are of the same length). Each of these lengths is called a "section", and the floor plan shown in Fig. 5.2 includes six different sections or wall groups. The identical wall lengths in each section lead to repetitive processes and less operational complexity both during factory production and onsite construction. As evident, the lengths of different sections are interrelated and, thus, are subject to design optimisation. This is especially the case in CLT buildings, where design optimisation determines the number and length of panel cuts and, subsequently, the cut waste in the manufacturing phase.

DfMA prescribes a set of design guidelines to simplify the manufacturing and assembly of products [179]. This concept mainly addresses the waste in production and increases the swiftness of material flow in production processes. According to the theory of swift even flow, waste reduction in processes can lead to an overall decrease in construction productivity [67]. Table 5.1 shows general DfMA guidelines enumerated in the literature [180, 25]. This table shows general rules that are applicable in different industry contexts regardless of the product and processes, as suggested by Bogue [181].

For the purpose of this research, material waste and standardisation of wall components have been chosen as design objectives. These principles have been incorporated into the objective function of the mathematical model as formulated by eq. 3), and is discussed in the next section. Some of these principles are not addressed by either the model or the CLT system since they are out of the scope of this research. Principles such as 6, 11, 12, and 13 in Table 5.1 are applicable in later stages of the design, where more details are determined.

Table 5.1: The current framework's scope

| Guideline | Addressed | | Not addressed | |
|---|---|---|---|---|
| | By the framework | By the CLT system | Later design stages | Not applicable on structural CLT |
| 1. Minimize the part count | | ✓ | | |
| 2. Standardize parts or use off the shelf components | ✓ | | | |
| 3. Minimize material waste | ✓ | | | |
| 4. Minimize material variety | ✓ | | | |
| 5. Design for ease of fabrication | ✓ | ✓ | | |
| 6. Minimize the number of connections | | | ✓ | |
| 7. Consider design for automated/robotic assembly | | ✓ | | |
| 8. Consider using modular design | | ✓ | | |
| 9. Design for simple component handling | | ✓ | | |
| 10. Use as few dissimilar materials as possible | | ✓ | | |
| 11. Minimize the use of fragile parts | | | ✓ | ✓ |
| 12. Do not over-specify tolerances or surface finish | | | ✓ | |
| 13. Aim for mistake-proof design | | | ✓ | |
| 14. Design for simple part orientation and handling | | ✓ | | |
| 15. Design with predetermined assembly technique in mind | | ✓ | | |

Simultaneously, the choice of the CLT system also contributes to the DfMA objectives. CLT is a non-volumetric modular preassembly system that provides easier transportation, simpler production and handling, and higher design flexibility compared to the volumetric modular system [215]. Therefore, this system is in line with DfMA guidelines due to its modular design (principle 8) and the automated handling of components (principles 7, 9, 14 and 15).

Standardisation of CLT panels is in line with DfMA principle 2 and is one of the objectives of the current framework. Concurrently, it acts as a proxy for a number of other principles by reducing manufacturing complexity (principle 5). Moreover, it can lower storage costs in the manufacturing plant and improve the quality of the manufactured product. A similar result will be observed in assembly tasks, where repetitive and non-various assembly tasks lead to a better learning curve for the assembly team. Standardisation of CLT panels also induces standardisation in transportation and onsite assembly operations through repetitive processes.

Further, CLT is a relatively expensive material compared to other conventional building materials, but it becomes economically viable due to its quick and easy onsite assembly. Thus, material waste reduction plays a key role in gaining a competitive advantage for CLT and increasing its adoption in the building industry. The model developed in this research accounts for material waste (DfMA principle 3) by reducing leftovers of a standard billet after cutting the required wall panels. To achieve this, all wall panels used on different building levels have to be optimally cut from different CLT billets. This is further discussed in "the bin packing process and the objective function" section.

## 5.5 DfMA-enabled modelling and optimisation of the CLT wall systems

The mathematical representation of the preliminary CLT wall design problem is highly similar to the BPP [165], which is a well-known problem formulation in operations research. Given a number of bins with fixed capacities and a number of items with different sizes, the goal of BPP is to find an arrangement of these items that requires the minimum number of bins to contain them. BPP is mathematically expressed as follows:

$$\text{Minimise } Z = \sum_j y_j \tag{5.1}$$

Subject to

$$\sum_i w_i x_{ij} \le c y_i \tag{5.2}$$

$$\sum_j x_{ij} = 1 \tag{5.3}$$

Where $y_j$ is a binary variable determining if bin j is used or not, and $c$ is the fixed capacity of each bin. $w_i$ is the weight (size) of the item i, and $x_{ij}$ is a binary variable that is equal to 1 if item i is placed in bin j. The assumptions of BPP is similar to optimising CLT walls for generating minimum waste when cutting CLT wall panels from fixed-size CLT billets.

In the current study, each floor of a CLT building is divided into sections, and each section is divided into spans, as shown in Fig. 5.2. Length of each section is equal to the length of the corresponding CLT wall. Also, due to structural limitations, the wall section location and lengths often remain the same on all levels, but the wall thicknesses can change. Therefore, the main design challenge is to find the best section lengths (L1 to L6 Fig. 5.2) within the length range given by the architect. These lengths lead to minimum total material waste after being cut from the corresponding billet types (Fig. 5.3). The CLT wall thickness is not subject to optimisation because it is usually dictated by the wall-to-wall distances determined by the architect, as discussed earlier.

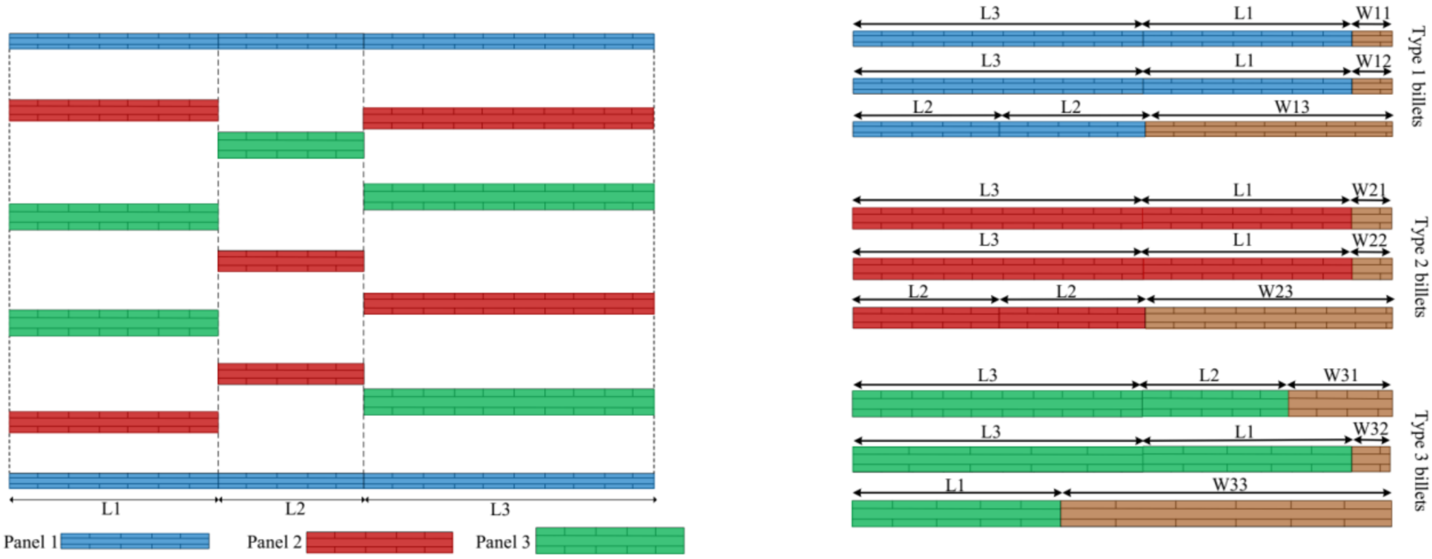



Figure 5.3: Example scenario of CLT wall optimisation problem; the determined section lengths (L1-L3) and the resulting wall lengths (left), and the optimum cutting plan (optimisation variable) on different billet types imposing minimum amount of wastes ($W_{mn}$)

Fig. 5.3 shows an example of the current optimisation problem for a single building level. The other levels will follow a similar length and location with potentially different wall types. Nonetheless, there are differences between this problem and the BPP:

- The generic BPP usually includes one material type, while the CLT wall design problem considers different material/stock types (shown by different colours in Fig. 5.3).
- The size of the orders (cut lengths) are fixed in a BPP, while in the current problem, these sizes are variables subject to optimisation in the problem.

Therefore, this problem hybridises a greedy algorithm and a GA to find the best section lengths and the arrangement of cuts on the billets. The GA leads the solution towards the global optimum, while the binpacking package uses the greedy search method to find the best cut plan for each generated solution. A summary of the solution generation and evaluation process employed in the python program is shown in Fig. 5.4.

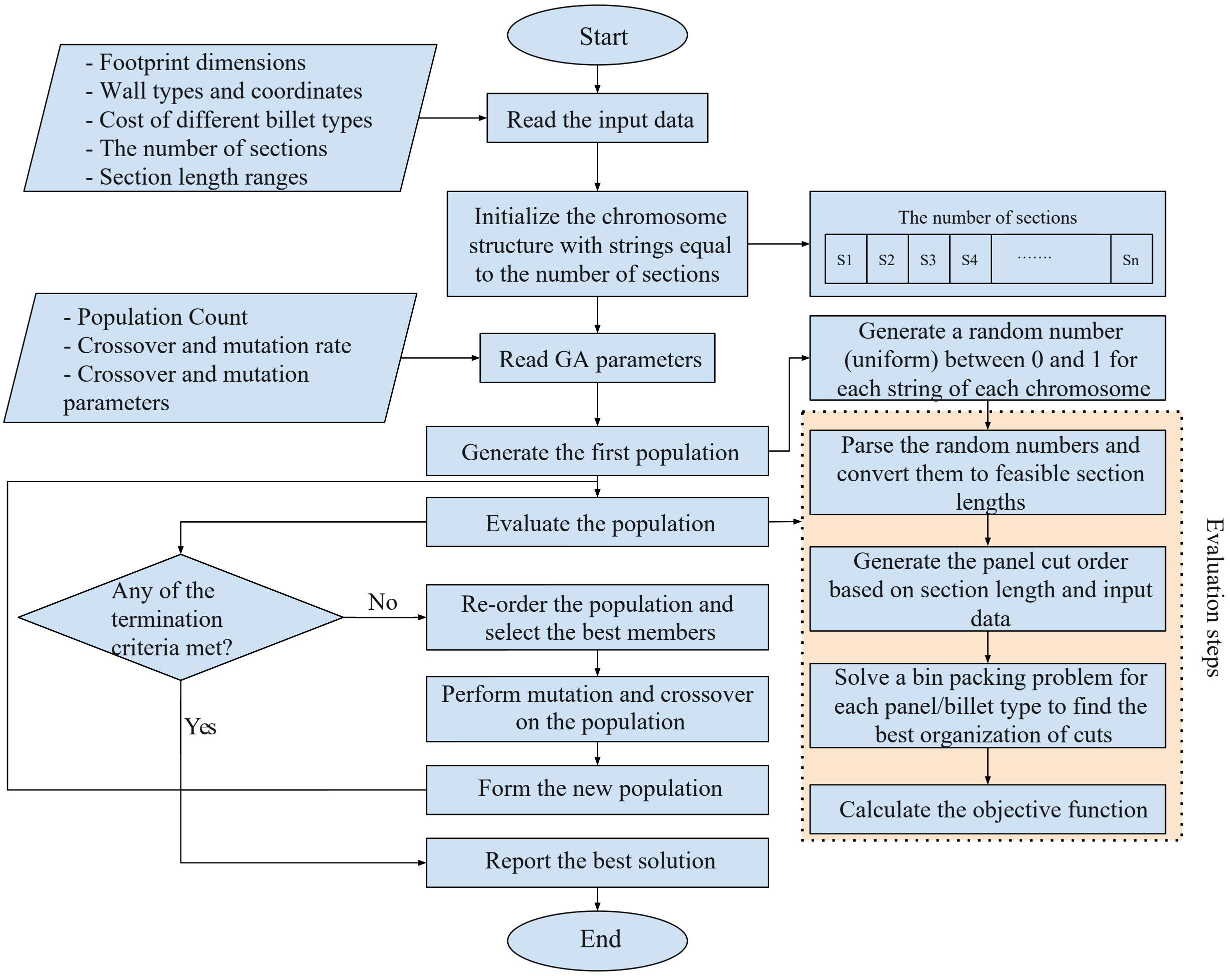



Figure 5.4: Overview of the optimisation process utilised by the framework

As seen in Fig. 5.4, the input parameters needed for initialising the optimisation involve building dimensions and the arrangement of different walls in the building, i.e., their level, section and their position in the section (extracted from S1 to S4 in Fig. 5.2). For this purpose, a python class "Walls" is defined with object variables, as shown in Fig. 5.5. By entering the input parameters, including walls' coordinates, section and type. An empty nested list ($Wall_{i,j,k}$) is created in python, with all elements in this list belonging to the "Walls" class.

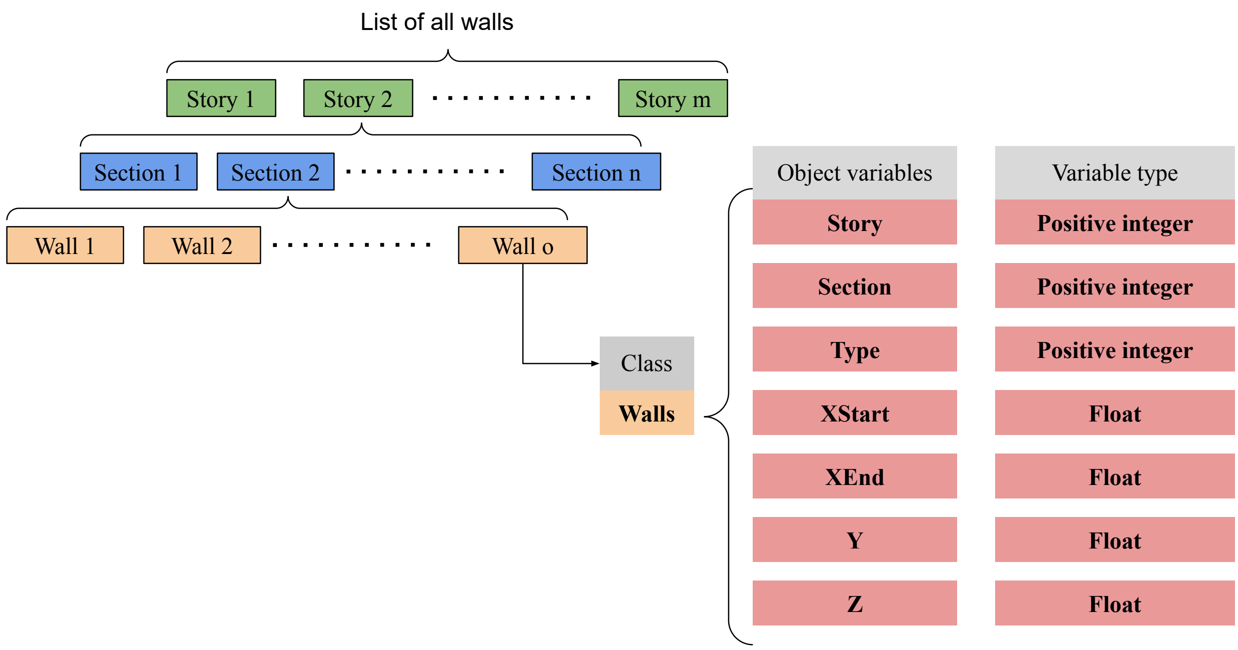



Figure 5.5: Problem inputs structure

### 5.5.1 Optimisation constraints

The notations used throughout this chapter are shown in Table 5.2.

Table 5.2: Notations

| Symbol | Description | Symbol | Description |
|---|---|---|---|
| $BL$ | Standard billet length | NS | The number of sections (wall groups) |
| $FL$ | Total length of the building floor plan | Npop | The number of GA population |
| $H_i$ | The floor to floor height of level $i$ | $\mathrm{NP}_{j,t}$ | The number of panels of type $t$ located in section $j$ |
| $i$ | Set of all building levels | $\mathrm{P}_t$ | Unit price of panel type $t$ ($\$/m^3$) |
| $j$ | Set of all sections (shared among levels) | $t$ | Set of all different panel types used |
| $k$ | Index of walls in each section | $U$ | The number of unique $L_j$ values |
| $L_j$ | The length of section $j$ | $V$ | The objective function of the optimization problem |
| M | Constant weight of the variety term | $\mathrm{Wall}_{i,j,k}$ | $k^{\text{th}}$ wall element located on $i^{\text{th}}$ level and $j^{\text{th}}$ section |
| $\mathrm{Max}_j$ | Maximum length acceptable for section $j$ | $W_t$ | Total waste on billets of type $t$ ($m^3$) |
| $\mathrm{Min}_j$ | Minimum length acceptable for section $j$ | | |

After the GA initialises the chromosomes based on the number of sections (wall groups) in the building footprint, an empty set is created with NS (Number of Sections) empty values, which are copied Npop times to form the initial population of solutions or chromosomes. Each of these empty values is then assigned a uniform random number in the [0,1] interval (see Fig. 5.4). To assess the optimality of each solution in terms of the objective function, these raw solutions need to be parsed and transformed into real values for the section lengths. The parsing process progresses such that the following constraints hold:

$$Min_j \le L_j \le Max_j \qquad \forall j \tag{5.4}$$

$$\sum_j L_j = FL \tag{5.5}$$

Eq. 5.4 and Eq. 5.5 define the real-world physical constraints of the problem. Eq. 5.4 restricts the length of each section to the range dictated by the architect, and Eq. 5.5 ensures that the summation of all section lengths is equal to the building floor length.

### 5.5.2 The bin packing process and the objective function

After the parsing process is finished, a list of all required cut lengths will be generated for each panel type, as shown in the below example:

$$\text{Cut list for panel type T} = [\overbrace{L_1 L_1 ... L_1}^{NP_{1,T}} \overbrace{L_2 L_2 ... L_2}^{NP_{2,T}} ...... \overbrace{L_n L_n ... L_n}^{NP_{n,T}}] \tag{5.6}$$

This list is used as the input for the bin-packing python package, which uses a greedy algorithm [216] with a relatively fast computation time to find the best cutting plan. Therefore, the binpacking algorithm will be run |t| times for each member of the population to find the best cutting plan for each material type (Wall types in this case). The result of this algorithm will be a detailed cutting plan, and the minimum required number of billets to achieve the order cut list.

This part of the algorithm will specifically minimise the material waste variable, as one of the DfMA principles discussed earlier. For every set of lengths automatically generated for the wall groups, the final amount of material waste caused by cuts will automatically be the minimum. An example of the final solution will be presented in the case study section. Using the cutting plan, the total amount of waste on each billet type can be calculated. This, in conjunction with the size variety factor, constitutes the objective function which is formulated as follows:

$$U = \sum_t W_t \times P_t + M \times U \tag{5.7}$$

The first term of Eq. 5.7 ($\sum_t W_t \times P_t$) is equal to the total amount of wasted material based on the cutting plan solution and billet type's unit price and represents the material waste variable (DfMA principle 3). The second term in Eq. 5.7 ($M \times U$) equals the number of different panel lengths with a constant weight as its multiplier, which leads the search toward more standard lengths (DfMA principle 2).

### 5.5.3 Initialisation of the walls class instances

Once the objective function has been set, a GA is initialised. The GA uses a set of genetic operators iteratively on an initial solution to generate new solutions converging to an optimum based on the given objective. Since the optimisation variables are real numbers, the study employs arithmetic crossover [171] and Gaussian mutations [157] as the genetic operators. After finding the global optimum, a single nested list is generated based on the structure presented in Fig. 5.5. $XStart$ and $XEnd$ variables for all wall elements are assigned as illustrated in Eq. 5.8 to Eq. 5.11.

Also, the floor level and Z variables will be assigned based on Eq. 5.12 to Eq. 5.15.

$$Wall_{i,j,k}.XStart = 0 \qquad \forall i,k \text{ and } j = 1 \tag{5.8}$$

$$Wall_{i,j,k}.XEnd = L_1 \qquad \forall i,k \text{ and } j = 1 \tag{5.9}$$

$$Wall_{i,j,k}.XStart = Wall_{i-1,j,k}.XEnd \qquad \forall i,k \text{ and } j > 1 \tag{5.10}$$

$$Wall_{i,j,k}.XEnd = Wall_{i,j,k}.XStart + L_j \qquad \forall i,k \text{ and } j > 1 \tag{5.11}$$

$$Wall_{i,j,k}.Story = 1 \qquad \forall j,k \text{ and } i = 1 \tag{5.12}$$

$$Wall_{i,j,k}.Story = Wall_{i-1,j,k}.Story + 1 \qquad \forall j,k \text{ and } i > 1 \tag{5.13}$$

$$Wall_{i,j,k}.Z = 0 \qquad \forall j,k \text{ and } i = 1 \tag{5.14}$$

$$Wall_{i,j,k}.Z = Wall_{i-1,j,k}.Z + H_{i-1} \qquad \forall j,k \text{ and } i > 1 \tag{5.15}$$

Eq. 5.8 sets the X value of the starting point of all walls in the first section to 0, and Eq. 5.9 sets the X of the endpoint of the walls in the first section equal to the section's length. Similarly, Eq. 5.10 and Eq. 5.11 set the starting point and ending point of all other walls based on the length of the sections they are located at. Eq. 5.12 and Eq. 5.13 set the values of the "Story" variable as ascending positive integers, and Eq. 5.14 and Eq. 5.15 assign the Z coordinates of each wall based on the floor heights of the below levels starting from 0.

Conforming with the goals of DfMA, the formulation introduced in this section involved constraints integrating both manufacturing and assembly considerations in deciding wall lengths as a building design variable. In detail, the bin-packing algorithm addresses the product waste in the manufacturing phase, while the standardisation objective in Eq. 5.8 addresses the process waste. Further, the defined wall class and the detailed interrelation among walls, as formulated in Eq. 5.8 to Eq. 5.15, ensure the incorporation of assembly constraints in the formulation. In the next section, the process of creating the BIM model for visualising the optimal solution is discussed.

### 5.5.4 Building Modelling and Visualisation

Once the optimum wall panels have been identified, the wall data are organised using the "Walls" class and are transferred to the Autodesk Dynamo platform. It should be noted that direct python coding in the Dynamo software is possible through python scripts. However, Dynamo uses IronPython, which does not support many additional python packages such as NumPy and binpacking. Also, it is not possible to export visual outputs from loops in iterative processes using the python script in Dynamo. Due to these reasons, the PyCharm code editor software was utilised to implement the optimisation algorithm, and the outputs were transferred to Dynamo using a Microsoft Excel file. An example of this file is shown in Fig. 5.6. The class structure created in the previous section is utilised for extracting this organised output. Each row of this spreadsheet is associated with a single wall and contains necessary information such as coordinates, wall type, story and section (wall group).

| Index | StartPoint | EndPoint | Y | Z | Type | Story | Sections |
|---|---|---|---|---|---|---|---|
| 1 | 0 | 10.5 | 0 | 4.5 | 105 | 2 | 1 |
| 2 | 0 | 10.5 | 5.8 | 4.5 | 115 | 2 | 1 |
| 3 | 0 | 10.5 | 11.2 | 4.5 | 115 | 2 | 1 |
| 4 | 0 | 10.5 | 16.6 | 4.5 | 115 | 2 | 1 |
| 5 | 0 | 10.5 | 22.4 | 4.5 | 105 | 2 | 1 |
| 6 | 10.5 | 14.5 | 0 | 4.5 | 105 | 2 | 2 |
| 7 | 10.5 | 14.5 | 4.5 | 4.5 | 115 | 2 | 2 |
| 8 | 10.5 | 14.5 | 8.7 | 4.5 | 115 | 2 | 2 |
| 9 | 10.5 | 14.5 | 13.7 | 4.5 | 115 | 2 | 2 |
| 10 | 10.5 | 14.5 | 17.9 | 4.5 | 115 | 2 | 2 |
| 11 | 10.5 | 14.5 | 22.4 | 4.5 | 105 | 2 | 2 |
| 12 | 14.5 | 17 | 0 | 4.5 | 105 | 2 | 3 |
| 13 | 14.5 | 17 | 4 | 4.5 | 115 | 2 | 3 |
| 14 | 14.5 | 17 | 18.4 | 4.5 | 115 | 2 | 3 |
| 15 | 14.5 | 17 | 22.4 | 4.5 | 105 | 2 | 3 |
| 16 | 17 | 19.5 | 0 | 4.5 | 105 | 2 | 4 |
| 17 | 17 | 19.5 | 4 | 4.5 | 115 | 2 | 4 |
| 18 | 17 | 19.5 | 18.4 | 4.5 | 115 | 2 | 4 |
| 19 | 17 | 19.5 | 22.4 | 4.5 | 105 | 2 | 4 |
| 20 | 19.5 | 23.5 | 0 | 4.5 | 105 | 2 | 5 |
| 21 | 19.5 | 23.5 | 4.5 | 4.5 | 115 | 2 | 5 |
| 22 | 19.5 | 23.5 | 8.7 | 4.5 | 115 | 2 | 5 |
| 23 | 19.5 | 23.5 | 13.7 | 4.5 | 115 | 2 | 5 |
| 24 | 19.5 | 23.5 | 17.9 | 4.5 | 115 | 2 | 5 |
| 25 | 19.5 | 23.5 | 22.4 | 4.5 | 105 | 2 | 5 |
| 26 | 23.5 | 34 | 0 | 4.5 | 105 | 2 | 6 |
| 27 | 23.5 | 34 | 5.8 | 4.5 | 115 | 2 | 6 |

Sheet1

Figure 5.6: Excel spreadsheet output of the Python optimisation results

The first step toward creating the information model is importing or creating the Revit families for the CLT components that are going to be used in the Revit project. There are a few downloadable options available online provided by CLT manufacturers. However, for the purpose of this research, since the only required component details are associated with the size and unit cost, the required CLT family is manually created in the Revit project environment. Fig. 5.7 shows the developed visual program and python script in detail.

As the initial step, the Revit nodes library is imported in a script in Dynamo to create parametric objects and elevations. The imported data from the Excel spreadsheet is labelled and assigned to empty lists for creating Dynamo and Revit objects. To create and place building components, building elevations need to be created, which is preferably done through a python script, to maintain model adaptability. Where applicable, the input data is converted to Dynamo format (e.g., the wall types and levels). Using the wall coordinates data, endpoints of the wall and the line connecting them are created. All aforementioned data are used to create Revit wall objects, which can be used for further data sharing and analysis through the capabilities of this software.

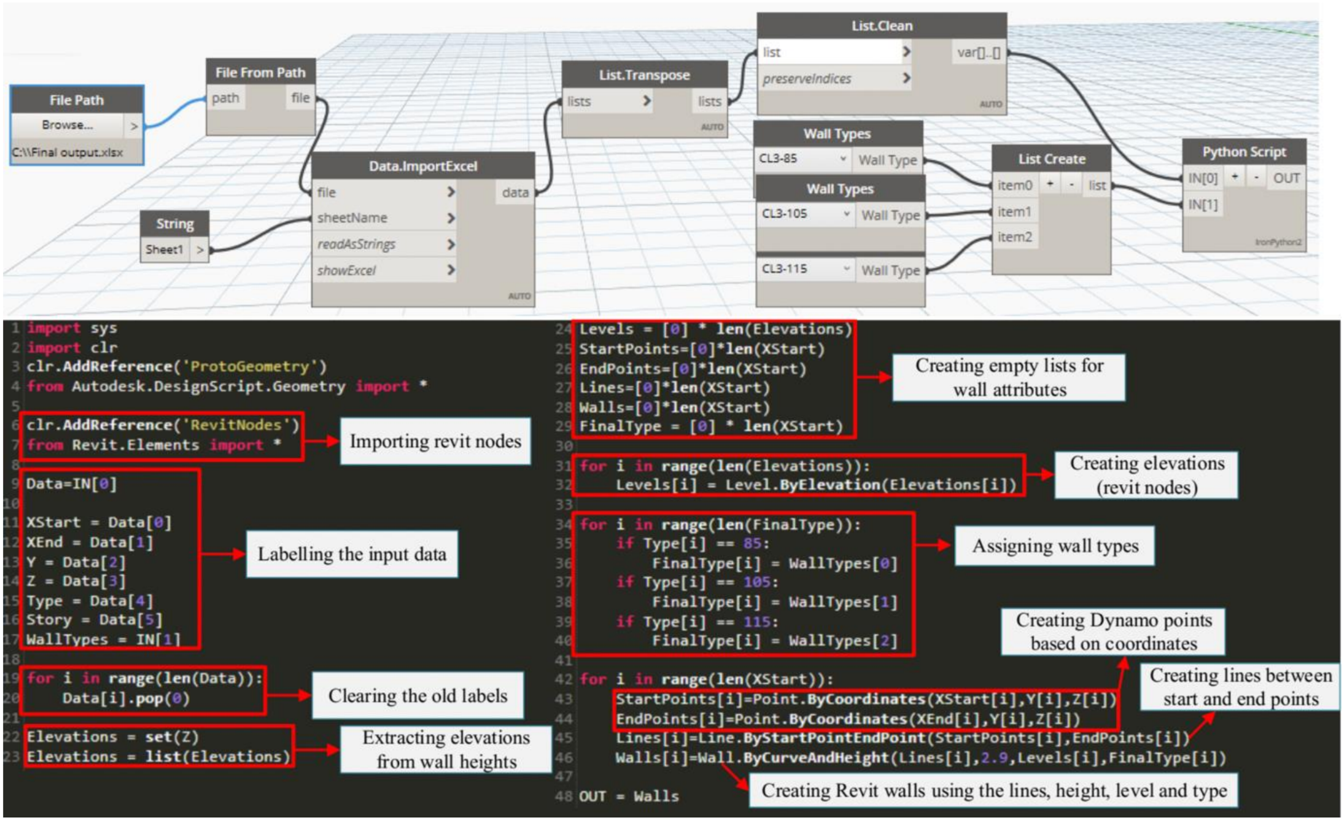



Figure 5.7: Dynamo visual program and script developed to convert optimisation results into Revit model

## 5.6 Case project

A case project is used to illustrate the application of the proposed design optimisation and visualisation framework. The project characteristics have been extracted from the example case project presented in Woodard and Jones [162]. The example project is an 8-storey building including seven timber apartment levels and a concrete retail level and basement, with a total height of 26.2 m and a $34m \times 22.5m$ footprint dimensions (Breadth×Depth), in an east-to-west orientation. The floor-to-floor height is 4.5 m for the retail level and 3.1 m for other levels. Since the retail level uses concrete materials, only the apartment levels are considered for modelling. The wall breakup plan for all apartment levels of the building is presented in Fig. 5.2.

Based on the spans supported by each load-bearing CLT wall, the building uses four load-bearing wall types, as well as one shear wall. Since the shear walls do not support vertical loads, and their length does not affect load-bearing wall lengths, they have been excluded from the optimisation model. Each wall type can take different sizes depending on the floor level, as presented in Table 5.3. For the purpose of optimisation, it is assumed that each of the wall sections (L1 to L6 in Fig. 5.2) can vary within a two-meter length difference between a minimum and a maximum acceptable length, as presented in Table 5.5.

Table 5.3: Wall panel sizes for different wall types [162]

| | WT1 | WT2 | WT3 | WT4 |
|---|---|---|---|---|
| Roof | CL3 - 85 | CL3 - 85 | CL3 - 85 | CL3 - 85 |
| 7 | CL3 - 85 | CL3 - 85 | CL3 - 85 | CL3 - 85 |
| 6 | CL3 - 85 | CL3 - 105 | CL3 - 85 | CL3 - 105 |
| 5 | CL3 - 85 | CL3 - 105 | CL3 - 105 | CL3 - 105 |
| 4 | CL3 - 85 | CL3 - 105 | CL3 - 105 | CL3 - 105 |
| 3 | CL3 - 105 | CL3 - 115 | CL3 - 105 | CL3 - 115 |
| 2 | CL3 - 105 | CL3 - 115 | CL3 - 115 | CL3 - 115 |

Table 5.4: Acceptable length ranges for each wall section in Fig. 5.2

| Section | L1 | L2 | L3 | L4 | L5 | L6 |
|---|---|---|---|---|---|---|
| Min.Length | 8 | 3 | 2.5 | 2.5 | 3 | 8 |
| Max.Length | 10 | 5 | 4.5 | 4.5 | 5 | 10 |

Table 5.5: Price of different panel sizes

| Panel size | Price($AUD/m^2$) |
|---|---|
| CL3-85 | 133 |
| CL3-105 | 160 |
| CL3-115 | 176 |

The building uses 30 vertical load-bearing CLT wall panels on each level and a total of 210 panels for the entire project. Table 5.3 shows three different panel sizes are used across all building levels (CL3-85, CL3-105 and CL3-115). A price estimate has been assumed for the unit area of each panel size, as reported in Table 5.5. In addition, all billets are assumed to be 16 meters long while their widths are equal to the corresponding floor height.

The input data were entered into the optimisation algorithm developed in the PyCharm environment to test two different scenarios: (i) The size variety term's multiplier (M) is set to 200 to enforce size standardisation in the solution search process, and (ii) The variety multiplier is set to zero, so that the algorithm prioritises the cut waste on billets and ignores standardisation. Subsequently, the code was run several times with various GA setups (i.e., the number of population, mutation and crossover rates). It was observed that for each of the above two scenarios, the optimisation converged to a similar solution for all algorithm setups, as reported in Table 5.6 to Table 5.8.

Table 5.6: Optimum section lengths

| Section | L1 | L2 | L3 | L4 | L5 | L6 |
|---|---|---|---|---|---|---|
| Lengths (standard) | 8 | 4 | 4 | 4 | 4.7 | 9.3 |
| Lengths (free) | 8 | 4 | 4.2 | 4 | 4 | 9.8 |

Table 5.7: Detailed panel cut plan for enforced standardisation

| Billet size | Cut plan | Billet size | Cut plan | Billet size | Cut plan | Billet size | Cut plan | Billet size | Cut plan |
|---|---|---|---|---|---|---|---|---|---|
| 85 | 9.3, 4.7 | 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 4.7,4.7,4.7 | 105 | 4, 4 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 4, 4, 4 | 115 | 8, 8 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4.7 | 85 | 4, 4, 4, 4 | 105 | 4, 4, 4 | 115 | 8, 8 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4.7 | 85 | 4, 4, 4, 4 | 105 | 4, 4, 4 | 115 | 8, 8 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 85 | 4, 4, 4, 4 | 105 | 4, 4, 4 | 115 | 8, 8 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 8, 8 | 105 | 4, 4, 4 | 115 | 8, 8 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 8, 8 | 105 | 4, 4, 4 | 115 | 8, 8 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 8, 8 | 105 | 4, 4, 4 | 115 | 8, 8 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 8, 8 | 105 | 4, 4, 4 | 115 | 8, 8 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 8, 8 | 105 | 4, 4, 4 | 115 | 8, 8 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 8, 8 | 105 | 4, 4, 4 | 115 | 4, 4, 4, 4 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 4.7,4.7,4.7 | 105 | 4, 4, 4 | 115 | 4, 4, 4, 4 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 4.7,4.7,4.7 | 105 | 4, 4, 4 | 115 | 4, 4, 4, 4 |
| 85 | 9.3, 4.7 | 85 | 9.3, 4 | 105 | 4.7,4.7,4.7 | 105 | 4, 4, 4 | | |

Table 5.8: Detailed panel cut plan for free optimisation

| Billet size | Cut plan | Billet size | Cut plan | Billet size | Cut plan | Billet size | Cut plan | Billet size | Cut plan |
|---|---|---|---|---|---|---|---|---|---|
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 85 | 9.8, 4 | 105 | 4.2,4.2,4.2 | 105 | 4, 4, 4,4 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 85 | 9.8, 4 | 105 | 4.2,4.2,4.2 | 115 | 8, 8 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 85 | 4, 4, 4, 4 | 105 | 4.2,4.2,4.2 | 115 | 8, 8 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 85 | 4, 4, 4, 4 | 105 | 4, 4, 4,4 | 115 | 8, 8 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 85 | 4, 4, 4, 4 | 105 | 4, 4, 4,4 | 115 | 8, 8 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 105 | 8, 8 | 105 | 4, 4, 4,4 | 115 | 8, 8 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 105 | 8, 8 | 105 | 4, 4, 4,4 | 115 | 8, 8 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 105 | 8, 8 | 105 | 4, 4, 4,4 | 115 | 8, 8 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 105 | 8, 8 | 105 | 4, 4, 4,4 | 115 | 8, 8 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 105 | 8, 8 | 105 | 4, 4, 4,4 | 115 | 8, 8 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 105 | 8, 8 | 105 | 4, 4, 4,4 | 115 | 4, 4, 4, 4 |
| 85 | 9.8, 4.2 | 85 | 9.8, 4 | 105 | 4.2,4.2,4.2 | 105 | 4, 4, 4,4 | 115 | 4, 4, 4, 4 |
| 85 | 9.8, 4 | 85 | 9.8, 4 | 105 | 4.2,4.2,4.2 | 105 | 4, 4, 4,4 | 115 | 4, 4, 4, 4 |
| 85 | 9.8, 4 | 85 | 9.8, 4 | 105 | 4.2,4.2,4.2 | 105 | 4, 4, 4,4 | | |

Table 5.6 shows the optimum section lengths found for both scenarios, which comply with the length ranges shown in Table 5.4 as dictated by the

architectural design. It was observed that both scenarios share similar section lengths, and both have used the same number of billets. However, when the total amount of waste is calculated based on the cost of the billets, the standard scenario and free scenario have produced 12.03% and 7.62%, respectively. This difference illustrates the formation of a local optimum in the solution space when the standardisation term is enforced. Although the free optimisation scenario has found the same number of various panel sizes, the search was not trapped in the first found optimum with maximum standardisation. The free optimisation could inherently reach maximum standardisation in the current case since the acceptable ranges for wall lengths included the numeric factors (8m, 4m) of the billet length (16m). This observation is in line with the real-world context, where manufacturers suggest designing in full billet lengths or factors of it and offer discounts to such designs as off-the-shelf options.

Table 5.7 and Table 5.8 show the optimal cutting plan, found using the greedy search algorithm by the binpacking python package. Each row in the column labelled "Cut Plan" shows different cuts on one billet of the corresponding size. For example, the second row of the second column in Table 5.7 shows that one of the CL3-85 billets will have two cuts with 9.3m and 4.7m lengths.

The optimisation results along with the component specifications were written into an excel file to be transferred into the Autodesk Dynamo environment. Using the script and visual program shown in Fig. 5.7, Revit walls were created in the Revit project environment, as shown in Fig. 5.8. Other details, including the floor panels and the first level, have been added for aesthetic purposes in Fig. 5.8.

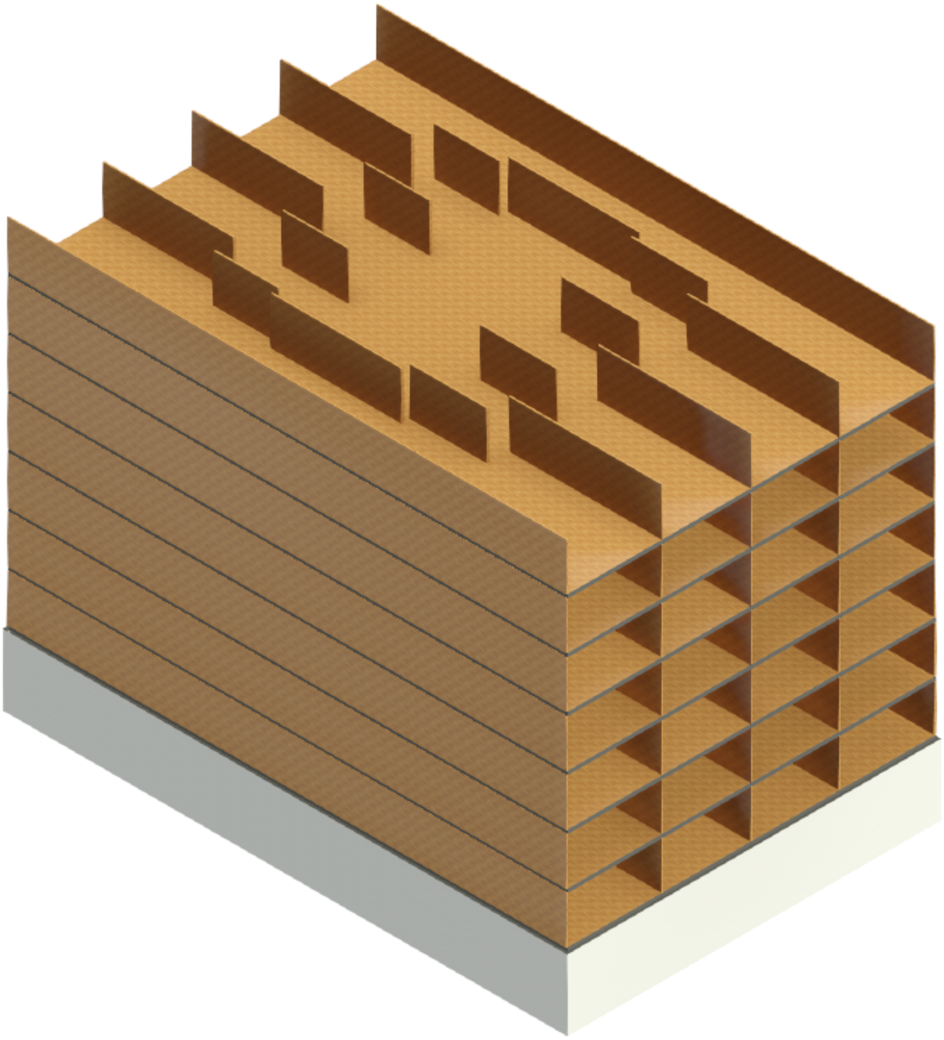


Figure 5.8: Visual output of the Dynamo script in Revit project environment

Using the generated information model, a bill of quantities for the CLT walls can now be generated. To this end, the schedule/quantities option of the Revit environment is used to enter a simple cost estimation formula. A snapshot of the resulting table is reported in Fig. 5.9 as an illustrative example.

The industry has reported 15% to 27% waste in cutting CLT panels from billets as the minimum amount achieved thus far [172, 173]. The results obtained by the model proposed in this research surpass this threshold under both of the aforementioned scenarios. Under the standardisation scenario, the CLT waste is reduced by approximately 3%, while under the free optimisation scenario, the reduction is more than doubled, being 8% less wasteful than the industry standard. This indicates the necessity of systematically applying DfMA principles to CLT building at early design stages rather than broadly taking DfMA into consideration at the factory production stage. In the latter approach, there is little flexibility or incentive to manipulate design for lowering CLT material cost and thus, a simple standardisation of CLT panels is pursued by CLT suppliers. The proposed model is capable of achieving standardisation simultaneous with waste minimisation, as can be evidenced by having only four standard panel sizes instead of the six standard panel sizes that are common in the industry.

<Bill of quantities>

| A | B | C | D |
|---|---|---|---|
| Family and Type | Area | Cost | TotalCost |
| | | | |
| Basic Wall: CL3-105 | 23.20 m$^2$ | 160.00 | 3712.00 |
| Basic Wall: CL3-115 | 23.20 m$^2$ | 176.00 | 4083.20 |
| Basic Wall: CL3-115 | 23.20 m$^2$ | 176.00 | 4083.20 |
| Basic Wall: CL3-115 | 23.20 m$^2$ | 176.00 | 4083.20 |
| Basic Wall: CL3-105 | 23.20 m$^2$ | 160.00 | 3712.00 |
| Basic Wall: CL3-105 | 11.60 m$^2$ | 160.00 | 1856.00 |
| Basic Wall: CL3-115 | 11.60 m$^2$ | 176.00 | 2041.60 |
| Basic Wall: CL3-115 | 11.60 m$^2$ | 176.00 | 2041.60 |
| Basic Wall: CL3-115 | 11.60 m$^2$ | 176.00 | 2041.60 |
| Basic Wall: CL3-115 | 11.60 m$^2$ | 176.00 | 2041.60 |
| Basic Wall: CL3-105 | 11.60 m$^2$ | 160.00 | 1856.00 |
| Basic Wall: CL3-105 | 11.60 m$^2$ | 160.00 | 1856.00 |
| Basic Wall: CL3-115 | 11.60 m$^2$ | 176.00 | 2041.60 |
| Basic Wall: CL3-115 | 11.60 m$^2$ | 176.00 | 2041.60 |
| Basic Wall: CL3-105 | 11.60 m$^2$ | 160.00 | 1856.00 |
| Basic Wall: CL3-105 | 11.60 m$^2$ | 160.00 | 1856.00 |
| Basic Wall: CL3-115 | 11.60 m$^2$ | 176.00 | 2041.60 |
| Basic Wall: CL3-115 | 11.60 m$^2$ | 176.00 | 2041.60 |
| Basic Wall: CL3-105 | 11.60 m$^2$ | 160.00 | 1856.00 |
| Basic Wall: CL3-105 | 13.63 m$^2$ | 160.00 | 2180.80 |
| Basic Wall: CL3-115 | 13.63 m$^2$ | 176.00 | 2398.88 |
| Basic Wall: CL3-115 | 13.63 m$^2$ | 176.00 | 2398.88 |
| Basic Wall: CL3-115 | 13.63 m$^2$ | 176.00 | 2398.88 |
| Basic Wall: CL3-115 | 13.63 m$^2$ | 176.00 | 2398.88 |
| Basic Wall: CL3-105 | 13.63 m$^2$ | 160.00 | 2180.80 |
| Basic Wall: CL3-105 | 26.97 m$^2$ | 160.00 | 4315.20 |
| Basic Wall: CL3-115 | 26.97 m$^2$ | 176.00 | 4746.72 |
| Basic Wall: CL3-115 | 26.97 m$^2$ | 176.00 | 4746.72 |
| Basic Wall: CL3-115 | 26.97 m$^2$ | 176.00 | 4746.72 |
| Basic Wall: CL3-105 | 26.97 m$^2$ | 160.00 | 4315.20 |
| Basic Wall: CL3-105 | 23.20 m$^2$ | 160.00 | 3712.00 |
| Basic Wall: CL3-115 | 23.20 m$^2$ | 176.00 | 4083.20 |
| Basic Wall: CL3-115 | 23.20 m$^2$ | 176.00 | 4083.20 |
| Basic Wall: CL3-115 | 23.20 m$^2$ | 176.00 | 4083.20 |
| Basic Wall: CL3-105 | 23.20 m$^2$ | 160.00 | 3712.00 |
| Basic Wall: CL3-105 | 11.60 m$^2$ | 160.00 | 1856.00 |

Figure 5.9: Illustrative example of generated bill of quantities

Moreover, generating a bill of quantities and cutting lists for CLT wall panels directly from the Revit BIM platform enables seamless and fast design data communication with other stakeholders. This can assist in avoiding errors and interoperability issues that are common when exchanging design information between designers, quantity surveyors, and factory production teams, each of which has its own digital platforms for managing building design.

## 5.7 Conclusions

The chapter introduced a framework as a design support tool for the DfMA-enabled design of CLT load-bearing wall systems. The proposed framework involves different aspects of the design activities, ranging from structural layout design optimisation to visualisation and generation of an information model for wall systems. The framework hybridised G-GA as a quick and effective technique to explore numerous design alternatives and find the optimum solution in terms of billet material waste and standardisation of CLT members as the target DfMA variables. Further, the process of data transfer into a BIM environment was developed and discussed in detail. This step plays a crucial role in verifying and proving the applicability of the design optimisation process.

The optimisation algorithm aims to improve factory production processes by incorporating main DfMA guidelines in the design decision-making process. The algorithm simultaneously minimises both panel size variety and billet waste caused by the subtractive production process of CLT panels. In doing so, it generates and evaluates various panel sizes, and calculates the resulting material and operational waste, to evaluate the design efficiency. While all the generated solutions met the building specifications and did not violate architectural requirements, the framework can identify a wall panelisation scenario optimal for manufacture and assembly.

The proposed model is beneficial in the early design stages due to the small design effort they require and the speed they offer in generating design solutions. The generated BIM model further assists the designer in collaborating with other project participants by providing a means for communicating early design solutions. The BIM model is anticipated to facilitate the feedback process from the early stages and help identify potential barriers to the implementation of DfMA. Further, the proposed framework also benefits manufacturers in aligning their production processes with preliminary design specifications.

Ideally, the design and supply-side work closely to develop a design with maximum performance in terms of the manufacturing and assembly process. However, in the project-based environment of construction, this ideal may not be completely achievable due to the high variability of the building products. This variability leads to temporary SCs for each project, making early communication and planning with the suppliers difficult for the design work. Implementing guidelines such as DfMA at the design stage ensures improvement in production processes since these rules are not project-specific.

The chosen arrangement of the load-bearing walls is a one-way spanning system, and this assumption may not be applicable in other cases. However, this system is the most common case in MT buildings [178] and is suggested as a better-performing solution [162]. Such limitations should be addressed in future research to expand the generalisability of the proposed model. Other potential areas of improvement include incorporating more details in terms of design specifications and considering wider aspects of the SC processes. A high potential for development exists in the area of logistics, where an automated design method can improve transportation and lifting processes by altering design variables.

# Chapter 6

# An Algorithm for Efficient Onsite Installation of Mass-Customised CLT Systems

## 6.1 Overview

The building industry has growingly adopted production-oriented approaches and prefabricated systems to improve its efficiency. In such a context, attaining efficient onsite operations is still a challenge and is constrained by lifting operations required for the installation of prefabricated systems. This issue particularly arises in MT multistorey buildings, as a new form of modular construction, circumscribed by various installation parameters. The literature, however, is slim in addressing the onsite challenges of installing prefabricated MT building systems. Therefore, this research proposes a novel framework for finding the optimal lifting and installation schedule that meets the stacking and handling requirements of CLT panels and different CLT panelisation configurations in an MT building layout. An evolutionary approach combined with a precise delay estimation algorithm is developed to find the optimal lifting sequence for luffing boom tower cranes in an example case. Results demonstrate the algorithm is capable of generating optimal lifting plans under different assembly scenarios better than industry benchmarks. The optimal scenario indicates a high level of interdependency between panelisation details and the assembly plan. As an effort to introduce further efficiency into the overall building production processes, this chapter extends the overall capabilities of the design systems introduced in the previous chapters, by proposing an assembly plan tailored for the specific context of CLT structures.

## 6.2 Introduction

The productivity gap between the building industry and other industrial sectors, such as manufacturing, is still considerable [217]. In recent decades, construction companies have adopted production-oriented approaches to fill this gap. In a production-oriented context, a large number of onsite activities are moved to the more controllable environment of factories where building systems are prefabricated [46]. Yet, there are inevitable operations occurring onsite to install the prefabricated systems. These operations involve storage, handling, lifting, and assembly of the prefabricated elements. Thus, despite highly efficient offsite production processes, the overall efficiency of such projects can be hindered by unproductive onsite processes.

In spite of endeavours to improve onsite assembly and installation processes, the building projects are still struggling to reach maximum onsite efficiency [218, 5]. This is because the building industry aims to maintain customisation rather than high standardisation in its prefabrication strategies and thus adopts MC to meet the market demands for non-identical and diverse building units [178]. Adopting MC, however, poses new constraints on achieving efficiency in onsite installation processes.

Using MC strategies, building companies design the final building by mixing a set of different prefabricated modules. An example of such modules is the CLT, a panelised structural system that lends itself to MC [178]. CLT panels are manufactured in different sizes in the factory and transported to the construction site for final assembly and installation.

While the planar nature of this system provides more flexibility for custom designs compared to volumetric systems with predefined spatial configurations, it can be more complex for on-site assembly due to the diversity of components and the required connections. Therefore, a precise plan is necessary to ensure smooth and time-efficient installation.

Crane is the leading resource in handling and lifting bulky and heavy prefabricated elements [219]. Thus, they play a crucial role in the efficient on-site installation of the offsite manufactured systems, such as CLT panels. However, poor crane scheduling and task assignment lead to wasteful lifting operations that adversely affect the overall efficiency of prefabrication. This means an inefficient onsite craning and installation may partially offset the efficiency that has been gained through the offsite factory production [220, 221].

Cranes can become a bottleneck in material handling for assembly operations and cause delays if they are not managed properly. Delays associated with crane operations can be minimised through optimum task scheduling, considering the kinematic details of the crane's motion [219, 222]. An effective crane schedule minimises unnecessary motions in between tasks and unproductive material handling [223].

The optimal tower crane operation has been addressed in the literature, commonly with two objectives: (1) Optimal motion path of the tower crane's hook between two predetermined points, in the presence of obstacles or other constraining conditions [224, 225], and (2) Optimal sequence of performing a set of predefined lifting tasks, each having certain supply and demand points [220, 223, 226, 227]. However, studies that concurrently consider multiple conditions, including the accessibility of the prefabricated items, interchangeability of such items and their availability at different supply points, a limited number of items in different staging areas, and installation interdependence constraints are scant. Such complex conditions govern CLT projects and require research to find an optimum lifting schedule.

In response to this, the present study develops an optimisation framework for task scheduling of a tower crane in a CLT building project. The developed framework can accommodate other prefabricated elements, including precast concrete and panelised steel systems. The framework models the kinematics of luffing tower cranes as a common choice for building construction in congested urban areas [228]. This makes the framework adaptable to other tower crane types, such as hammerhead cranes, with simpler motion scenarios. The model utilises a GA search method to find the optimal crane lifting schedule and uses a case building made of CLT panels to test and validate the framework.

## 6.3 Literature review

A wide range of articles has addressed crane planning in the past. Studies in this area are generally divided into two categories based on the two main types of cranes, i.e., mobile cranes and tower cranes [229]. Mobile crane planning methods predominantly focus on crane operation and path planning with little interest in location optimisation since they can be relocated [230]. On the other hand, tower crane planning papers address different topics, including model selection, crane location planning, crane path planning, and lifting sequence optimisation [230]. As tower cranes are more common in medium to high-rise construction projects [231], they have been chosen as the primary lifting equipment for the current study. Therefore, studies related to mobile cranes are not addressed in this section.

For the purpose of this research, path planning and lifting sequence optimisation are relevant since they deal with the dynamics of lifting operations. The crane path planning studies make efforts to model and optimise the motion path of the cranes mainly to attain a collision-free route as their primary objective and the shortest path or the motion time as their secondary objectives [230]. Lifting sequence optimisation studies, however, try to optimise the total lifting time, considering different variables such as the choice of source and destination and the sequence of the lifting operations [220, 232].

### 6.3.1 Crane path planning

The central objective of crane path planning is to find a collision-free movement path for transporting an item from a lifting point to a destination location across the construction site [233]. Initial research in this area began with a visualisation approach towards tackling the problem of crane collisions on-site as the main motivation of this field [234]. The visualisation studies intend to provide sufficient tools for visual inspection and understanding the physical obstructions that may prevent the straight or easy passage of the crane hook in the real construction site [235]. They consider information such as geometries of present obstacles, schedule, and crane specifications. More recent studies attempt to automate the entire process of crane operation by adopting the concept of configuration space (C-space) in the construction domain [236]. The main contribution of these studies is constructing more detailed C-spaces and introducing more efficient algorithms for searching the C-space [237, 238]. In the present study, such formulations are adapted to precisely estimate lifting delays associated with each solution identified for the crane task schedule.

More recent developments in this category aim at collision-free crane operations while eliminating the need for the visual inspection process proposed by the visualisation approaches. To achieve this, the developed mathematical models should consider relevant real-world scenarios and obstacle details [239, 240]. Cranes kinematics, obstructions location, and possible collision scenarios are modelled in three-dimensional space. To model cranes, a minimum of three different motion types, including hoisting, luffing and slewing, must be considered when calculating the motion [225]. Other dimensions, such as load sway and crane walking, could be added to make more precise estimations of the crane operation times [241]. In addition, the crane manufacturers provide product catalogues determining other constraints such as lifting load charts and allowable angles. These specifications are also incorporated in the model by formulating crane lifting capacity at different operating radii and boom lengths [240, 242]. Other specifications can also be accommodated into the mathematical model depending on the crane type or site conditions, such as safety envelop and moving objects [243].

### 6.3.2 Lifting sequence optimisation

The crane is one of the major space users on construction sites, and a better lifting sequence with lower lifting time leads to higher space utilisation which can improve the overall efficiency of the lifting operations [223, 227, 244]. This is important since the spatial correlation of the consecutive lift tasks can affect the non-loaded motion time of a crane required for moving its hook to the next lift [227, 231]. This plays a major role in prefabricated construction projects in which coordinated space utilisation is critical in obtaining shorter craning time [227]. In this research context, avoiding clashes among multiple operating lifts is also an important variable as it affects the total lifting time and the decision-making process due to higher complexity, particularly when multiple cranes operate concurrently.

Traditionally, the problem of lifting sequence optimisation is tackled through rule-of-thumb strategies, including First in First Served (FIFS), Shortest Job First (SJF), and Nearest Neighbour First (NNF) [227]. For more optimal results, however, the literature has gone beyond the rule of thumb by developing optimisation algorithms using dynamic programming [227], integer programming [232], and Tabu search [223]. This can be exemplified through the research conducted by Zavichi et al. [232], who introduced a modified Travelling Salesman Problem (TSP) formulation for optimising the lifting sequence of a tower crane with multiple storage locations. This model led to 25-45% time saving compared to the FIFS case. The model, however, does not address the circumstances pertaining to material availability and accessibility. Monghasemi et al. [220] employed an improved harmony search algorithm to find the best-performing lifting sequence regarding lifting request waiting times. This model does not address the operational complexity inherent in the onsite assembly and installation of panelised prefabricated systems in which stacking and storage conditions are variable and constrain the lifting operations [31, 245]. For instance, the loading point of each lifting task, where materials are stacked on the ground, is predetermined, which is not the case in CLT buildings and most prefabricated building projects. Farajmandi et al. [226] presented a module installation sequence optimisation algorithm based on a heuristic method. The developed algorithm performs a search for a group of predetermined lifting tasks while minimising unnecessary crane operation tasks. This model is valuable as it has been developed for a mobile crane, but it does not reflect the stacking and accessibility constraints that are often applied in a CLT building context. Wu et al. [223] introduced a Tabu search algorithm combined with a 4D simulation method to optimise and visualise multiple tower crane operations. In similar research, Wu and de Soto [227] integrated the motion kinematics of the crane with a dynamic programming technique to optimise the lifting sequence in a construction site serviced with two cranes. Both studies [223, 227] assumed predetermined lifting tasks and instant access to materials at staging areas. The reality of panelised prefabricated building construction, inclusive of CLT buildings, may violate such assumptions.

The objective of the current study is to find the optimum crane task schedule that minimises the total lifting time in building construction made of panelised prefabricated systems. The developed model adapts mathematical and computational procedures proposed by the lifting sequence optimisation literature to estimate the time associated with the lifting tasks. Still, it extends the body of knowledge by addressing additional complexities and constraints pertaining to site-specific staging, handling, and installation requirements. These include the accessibility of panels within a stack of panels, additional lifting required to reach a target panel, multiple staging areas, and interchangeability of panels when they can be used under different installation scenarios at different locations.

## 6.4 Methodology

In this section, first, the lifting time estimation algorithm is introduced, which takes into account the motion path, crane specifications, and load. Then the stepwise process of transforming randomly generated solutions into feasible loading paths and the evaluation algorithm is discussed. Finally, the discussion will move to testing the algorithms on a practical example for different sequencing preference scenarios in the results section.

### 6.4.1 Lifting time estimation

Calculation of the lifting time associated with the motion of the hook is estimated in two different modes of operation, i.e., loaded and no-load lifting. This consideration is essential since the movement of the hook is affected by its load and will be slower in the presence of loads. Companies that manufacture tower cranes provide catalogues containing charts and diagrams for detailed crane motion under different loads. The equations presented in this section are all applicable to different loading modes. However, the velocity of the hook should be entered as a function of the amount of load to obtain realistic time estimations. The lifting time estimation formulation introduced in this chapter is adopted from the literature [227, 246], with a few modifications to make it applicable to the present context. The lift number index has been removed from the original formulation since consecutive lift operations in the CLT context are more complex and require developing a separate algorithm. Therefore, the evolutionary algorithm will handle the entire lifting operations, and the original formulation is utilised to estimate the lifting time for a single lifting operation of a single crane.

The following notation is used throughout this section.

$(Cx, Cy, Cz)$ : Tower crane location coordinates

$(Sx, Sy, Sz)$ : Supply location coordinates

$(STx, STy, STz)$ : Transformed supply location coordinates

$(Dx, Dy, Dz)$ : Demand location coordinates

$T$ : Lifting motion time

$Tl$ : Loading time

$Tm$ : Loaded motion time

$Tu$ : Unloading time

$Th$ : Horizontal motion time

$Tv$ : Vertical motion time

$\beta$ : Vertical and horizontal motion coordination (between 0 and 1)

$T\omega$ : Boom slewing motion time

$\theta$ : Slewing angle

$V\omega$ : Slewing speed

$T\beta$ : Boom luffing motion

$\theta^*$ : Luffing angle

$V\beta$ : Luffing speed

$\alpha$ : Slewing and luffing motion coordination

$HD$ : Hoist motion distance of the hook

$V$ : Hoist speed of the hook

$BD$ : Boom vertical motion distance

$BL$ : Boom length

$L$ : Euclidian distance between the supply and demand points in the horizontal plane

$\rho(S)$ : Horizontal distance between crane and supply location

$\rho(ST)$ : Horizontal distance between crane and transformed supply location

$\rho(D)$ : Horizontal distance between crane and demand location

Fig. 6.1 shows the lifting parameters from both horizontal and vertical perspectives in which (Cx,Cy,Cz), (Sx,Sy,Sz), (Ex,Ey,Ez), and (STx,STy,STz) are the location of crane, lifting start point, lifting end point, and transformed lifting start point, respectively. The total lifting time is the summation of loading time (Tl), loaded motion time (Tm), and unloading time (Tu), as shown in Eq. 6.1:

$$T = Tl + Tm + Tu \tag{6.1}$$

Loaded motion time ($Tm$) is calculated using horizontal motion time ($Th$), vertical motion time ($Tv$) and motion coordination factor, as expressed in Eq. 6.2. The coordination factor determines the amount of horizontal and vertical motions performed simultaneously; 0 means completely simultaneous and 1 means completely consecutive. The value of this factor is usually set to 1. Horizontal motion time ($Th$) is determined by slewing motion time ($T\omega$), luffing motion time ($T\beta$), of the boom, and slewing and luffing motion coordination factor in the horizontal plane ($\alpha$) as expressed in Eq. 6.3. The $\alpha$ can vary between 0 and 1, meaning simultaneous or consecutive motion, respectively. This parameter is typically set to 0.25.

$$Tm = max(Th, Tv) + \beta \times min(Th, Tv) \tag{6.2}$$

$$Th = max(T\beta, T\omega) + \beta \times min(T\beta, T\omega) \tag{6.3}$$

Slewing motion time ($T\omega$) is determined by the slewing angle of the boom when moving from start point to end point, and by the slewing speed ($V\omega$), as shown in 6.4. Slewing angle ($\theta$) is calculated using Eq. 6.5 to Eq. 6.8. Boom luffing motion time ($T\beta$) is determined by the luffing angle from the transformed lifting start point to the lifting endpoint ($\theta^*$) and by luffing speed ($V\beta$), as expressed in

Eq. 6.9. Luffing angle ($\theta^*$) is calculated using Eq. 6.10 to Eq. 6.13.

$$T\omega = \frac{\theta}{V\omega} \tag{6.4}$$

$$\theta = \arccos\left(\frac{\rho(D)^2 + \rho(S)^2 - L^2}{2 \times \rho(D) \times \rho(S)}\right), 0 \leq \arccos\left(\frac{\rho(D)^2 + \rho(S)^2 - L^2}{2 \times \rho(D) \times \rho(S)}\right) \leq \pi \tag{6.5}$$

$$\rho(S) = \sqrt{(Sx - Cx)^2 + (Sy - Cy)^2} \tag{6.6}$$

$$\rho(D) = \sqrt{(Dx - Cx)^2 + (Dy - Cy)^2} \tag{6.7}$$

$$L = \sqrt{(Dx - Sx)^2 + (Dy - Sy)^2} \tag{6.8}$$

$$T\beta = \frac{\theta^\star}{V\beta} \tag{6.9}$$

$$\theta^\star = \left|\arccos\left(\frac{\rho(ST)}{BL}\right) - \arccos\left(\frac{\rho(D)}{BL}\right)\right|,$$

$$0 \leq \arccos\left(\frac{\rho(ST)}{BL}\right) \leq \pi, 0 \leq \arccos\left(\frac{\rho(D)}{BL}\right) \leq \pi \tag{6.10}$$

$$\rho(ST) = \sqrt{(STx - Cx)^2 + (STy - Cy)^2} \tag{6.11}$$

$$STx = Cx + \rho(S) \times \frac{Dx - Cx}{\rho(D)} \tag{6.12}$$

$$STy = Cy + \rho(S) \times \frac{Dy - Cy}{\rho(D)} \tag{6.13}$$

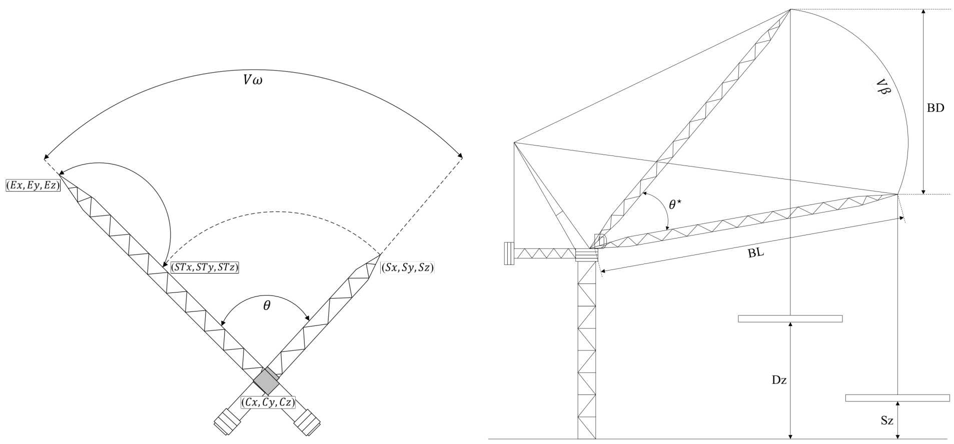



Figure 6.1: Loaded lifting in horizontal (left); and vertical planes (right)

Vertical motion time (Tv) is determined by the hoist motion distance of the hook from the lifting start point to the lifting endpoint (HD) and by the hoist speed of the hook (Vv), as expressed in Eq. 6.14. The hoist motion distance of the hook (HD) is determined by the height difference between the lifting endpoint (Dz) and lifting start point (Sz) and by boom vertical motion distance from the transformed lifting start point to the lifting endpoint (BD). Boom vertical motion distance (BD) is calculated using Eq. 6.15.

$$Tv = \frac{HD}{Vv} \tag{6.14}$$

$$BD = |\sqrt{BL^2 - (\rho(ST))^2} - \sqrt{BL^2 - (\rho(D))^2}| \tag{6.15}$$

Calculating the hook's hoist motion distance (HD) falls under three categories based on the comparison of the tower crane's horizontal distance from the supply point ($\rho(S)$) and the demand point ($\rho(D)$). If the distances are equal, then HD will be calculated using Eq. 6.16, while in other cases, the value of (HD) is calculated using three different scenarios. When the demand point is horizontally closer to the crane than the supply point ($\rho(S) > \rho(D)$)), the hoist motion distance (HD) is calculated using one of the cases in Eq. 6.17. In contrast, in case the supply point is horizontally closer than the demand point ($\rho(S) < \rho(D)$), the value of (HD) is calculated using one of the cases in Eq. 6.18.

$$HD = |Dz - Sz| \rho(s) = \rho(D) \tag{6.16}$$

$$HD = \begin{cases} |Dz - Sz| + BD & \text{if } \rho(S) > \rho(D) \text{ and } Dz - Sz \leq 0 \\ BD - |Dz - Sz| & \text{if } \rho(S) > \rho(D) \text{ and } 0 < Dz - Sz \leq BD \\ |Dz - Sz| - BD & \text{if } \rho(S) > \rho(D) \text{ and } BD < Dz - Sz \end{cases} \tag{6.17}$$

$$HD = \begin{cases} |Dz - Sz| + BD & \text{if } \rho(S) < \rho(D) \text{ and } Sz - Dz \leq 0 \\ BD - |Dz - Sz| & \text{if } \rho(S) < \rho(D) \text{ and } 0 < Sz - Dz \leq BD \\ |Dz - Sz| - BD & \text{if } \rho(S) < \rho(D) \text{ and } BD < Sz - Ez \end{cases} \tag{6.18}$$

## 6.5 Problem definition

The problem addressed in this chapter is to find an optimal panel lifting sequence that minimises the total time required for the entire lifting operation in any panelised prefabricated context, including MT buildings. CLT panels are shipped in the form of packs, stacked based on the size in descending order, and separated using dunnage. While effort is made to deliver each pack in a just-in-time approach, the order of stacking on trucks suits efficient and safe transport which is usually different from the order of assembly. Therefore, additional lifting operations are often required to access the specific panel scheduled to be installed at each lifting operation. As a result, the scheduling of the CLT structural components can be subject to optimisation, especially in the presence of handling operations in staging areas on the ground.

From this study's standpoint, the panels are already stored on-site for the entire floor level under construction. For simplicity, it is assumed that the hook starts operating from the location of the first panel to be lifted. After installing the first panel, depending on the accessibility of a target panel that must be installed next, one of the below scenarios can happen:

1. The target panel is on top of its stack and directly accessible by the hook: In this case, the hook moves vertically close to the panel where workers attach the hook block to the panel. Then, the crane performs a combination of motions (luffing, slewing, and vertical motions) to take the panel to its final installation location, where workers start the installation operation. The crane hook remains engaged until the installation is complete. Once completed, the crane is ready to return to the staging areas to start the next lifting operation.

2. The target panel is not on the top of its stack and thus, access to it is blocked by one or more top panels: This requires lifting and moving the top panel(s) to another staging area, returning to the stack where the target panel resides and is accessible. It is evident that the specifications of the supply locations will change dynamically as a new stack of panels will be created. This must be considered as a potential supply point for the subsequent lifting operations.

Based on the project conditions, including the buildings in the project's adjacency, site access, maximum load to be carried, and the building footprint area, different types of cranes may be chosen for the project. Generally, tower cranes are the proper lifting solution for mid- to high-rise buildings since they offer higher working height and longer operating radius [231]. This study assumes that the site uses a single crane for the lifting operation. Moreover, the study does not consider the just-in-time delivery of the panels. Instead, it assumes the panels required for the one-floor level have already arrived on-site and are stacked in storage locations. The onsite stacking order is the same as the order of panels stacked on the truck (i.e., large to small stacked from bottom to top as shown in Fig. 4.3.C). This is further discussed in the example scenario in the next section.

Another notable assumption in the model presented here is that the handling of the panels can be performed in stacks. In other words, the tower crane can lift a number of panels and unload them at another location, to access the target panel. This process can be repeated consecutively on each and every stack of panels, including on the new stacks created to access the target panel. Having all of the above assumptions established, the discussion now proceeds to explain the details of the lifting operations and the modelling process.

## 6.6 Problem modelling

The problem has three main entities: panels, demand points, and supply points each having its own characteristics. These entities are defined in the python program using classes and methods. The supply point entity, which is also referred to as the 'staging area', is any feasible location on the ground in which the panels are stacked. The demand point entity is any installation location on the building footprint, which is defined by a) the exact coordinates of its centre point and b) the panel structural specifications required for that location, including its geometry and thickness. The thickness is specified in terms of the number of layers required for the CLT panel and the thickness of each layer. The panel entity refers to the available panels and is defined by a) panel physical specifications (i.e., geometry and the number of CLT layers) and b) time-dependent specifications. The time-dependent specifications involve information about their current location status including the index of its corresponding stack, coordinates of the stack, and current position of the panel in the stack in denoting the panel's current accessibility.

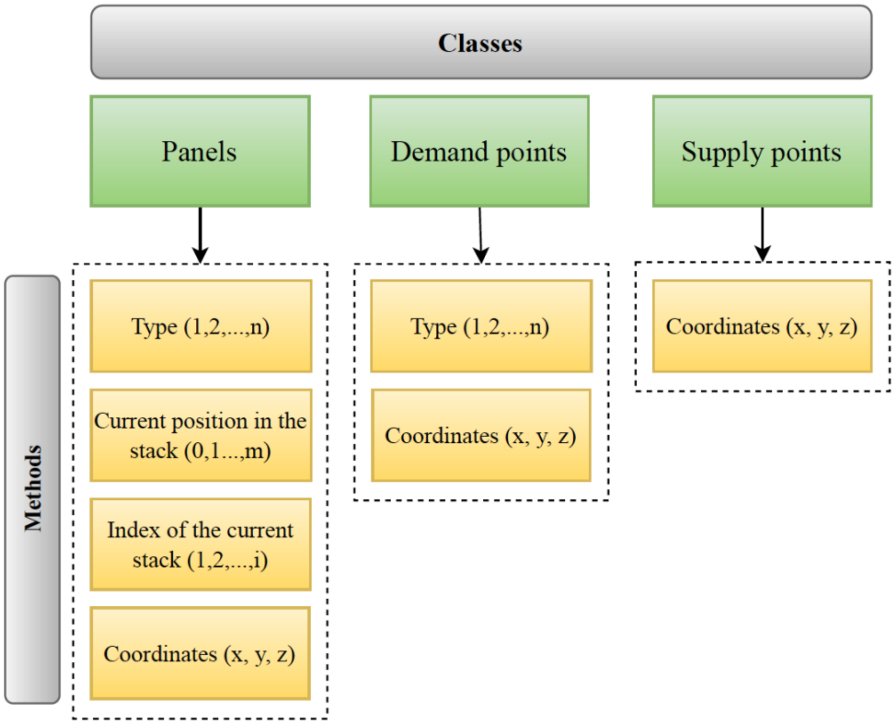



Figure 6.2: Different Classes and methods utilised for modelling the problem

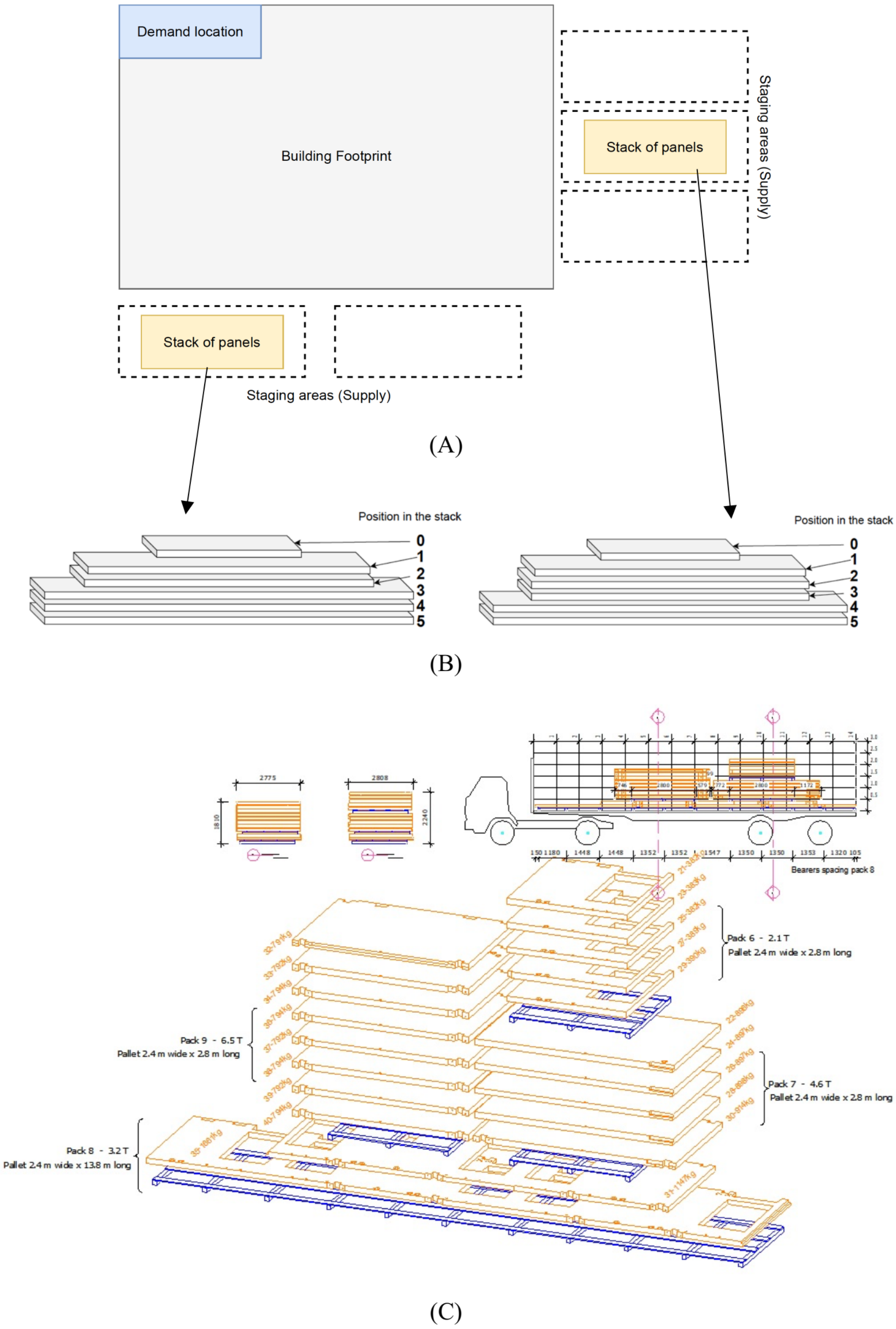



Figure 6.3: Visual demonstration of classes and methods: (A) site layout, (B) details of the stacks, and (C) Example of stacking for transportation (adopted from [247])

## 6.7 Results and discussion

As the aim is to identify the fastest panel installation sequence, the optimality of a sequence is measured in terms of total lifting time. A set of installation orders are predefined based on real-world scenarios, dictated by the structural engineers and planners. It should be noted that each installation scenario can be achieved through virtually countless lifting sequences of panels. Yet, the challenge is to identify which choice of lifting sequences of panels can lead to the shortest installation time.

## 6.8 Solution generation workflow

This section explains the process of generating random feasible solutions and identifying the optimal lifting sequence. The aforementioned classes and methods are python programming language terminologies used in this model to introduce different entities and their behaviours. In simple terms, a class is essentially a template for objects while methods are different procedures associated with a class. A summary of the classes and methods developed in the current model is shown in Fig. 6.2.

The supply points class only determines the points in the construction site, where the panels are either already stacked, or the space is available for future stacking. This class only has one method: three-dimensional coordinates of the supply locations centre, from an arbitrary origin point. The demands and panels both have a type method, distinguishing different panels based on their geometry by assigning them different indices. Further, both demands and panels class have a coordinates method, which shows the centre of the installation point and the panel's current location. In addition, the panels can also be stacked, which makes it necessary to give them a method describing the details of this behaviour. The potential locations of the stacks are given indices, which are introduced as a method for the panel class. Also, the panels are given an integer number based on their position in the stack, starting from the top (zero), and increasing for lower panels. An example of different classes and their instances is shown in Fig. 6.2.

The lifting operations planning process begins with identifying the chosen demand point to be satisfied at the current lifting operation. The model reads the "Type" value of the current demand point and goes through the stacks available across all supply points to find the panels with a similar type. Then, the model chooses a panel that not only satisfies the “Type” value but also has the most reachable position index (i.e., the one that is the fastest to reach) in each stack. If there are multiple panels that satisfy both conditions, then the model randomly chooses one of these panels to be lifted to and installed at the demand point. The exact duration of the lifting operations is then calculated considering the accessibility of the panel, the required double movements, and the lifting and positioning of the target panel to the installation location. This duration is subject to minimisation as the main objective function of the proposed framework and, the resultant lifting sequence becomes the optimum solution.

In the previous step, the panel that is chosen to be lifted can be either the top panel in the stack, or be placed lower and therefore, is not directly accessible. The latter case happens if the position index is not equal to zero. In this case, the tower crane performs a handling operation, moving the group of panels higher than the target panel, to the closest empty staging area so that the target panel is accessible. The crane moves back to the original stack again and performs the lifting operation to the demand point, similar to the first case where the target panel was readily accessible for lifting. The lifting operation continues with the crane moving to the next target panel, performing similar operations.

The programming process begins with utilising the classes and their methods to establish the inputs of the problem, which will then be used in the algorithm that generates the random feasible solutions. The first step is to enter the details of the panels stacked at different locations on the construction site, as instances of the "Panels" class. Then each panel needs to be associated with one of the staging areas as their initial location, and a position in their stacks, denoting the initial accessibility of the panel. The algorithm starts this process by reading the "Index of the current supply point" from each panel and setting the horizontal coordinates (x,y) of each panel equal to the coordinates of their corresponding staging area. In addition, the altitude of each panel (z) will be set based on the "Current position in the stack" and the required spacing between each couple of panels entered based on the technical requirements.

The next step for the algorithm is to generate the installation priority plan for the demand points or read it from an input list if required. This plan is in the form of a python list, containing the demand indices in the correct order of installation. For the purpose of this study, ordering algorithms have been developed to convert this list to a coordinate of each demand point. These algorithms will be discussed in the case study section. This list of demand points is then used as the basis of the rest of the solution generation algorithm as described in the below steps:

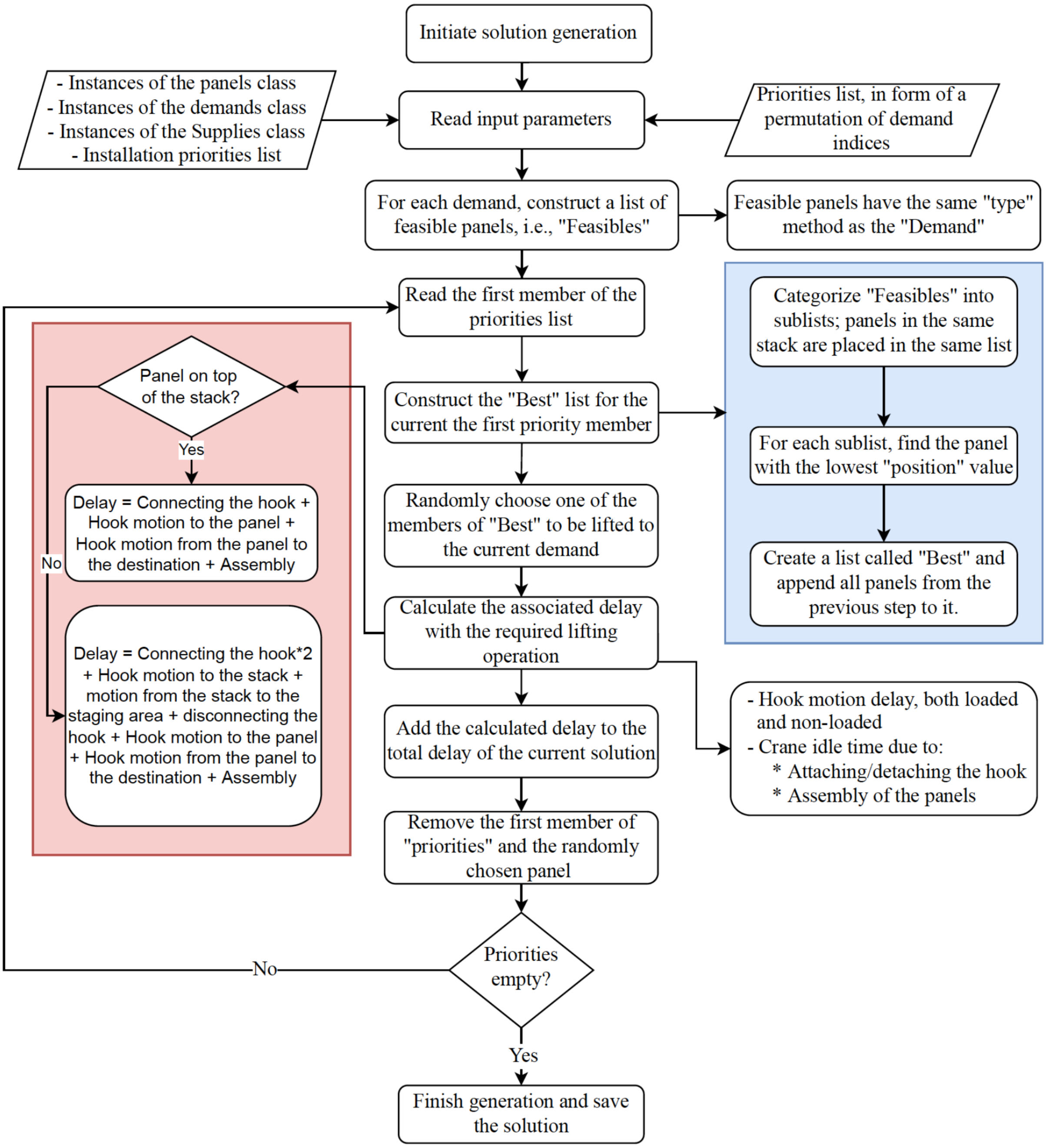



Figure 6.4: The process of random solution generation

A set of consecutive python functions have been developed to implement the proposed model in a programming environment. As shown in

Fig. 6.4, each function runs one part of the lifting sequence optimisation process by receiving inputs from the previous function and generating outputs that are used by the next function.

## 6.9 Case study

To validate the applicability of the model presented in this chapter, a real-world case project is chosen where some assumptions have been made either due to incomplete data or for simplicity. The building project is a panelised eight-story residential building with a total height of 26.2m. Currently, the seventh floor of the building is under construction, with a floor height of 20 meters. This floor requires a total of 28 floor panels of different sizes stored in three different stacks, in the available staging areas which must be lifted into the installation location. The staging areas and stacks are located on the north and east sides of the building, and the single tower crane is located on the north side of the construction site. A summary of the problem's inputs is shown in Fig. 6.5.

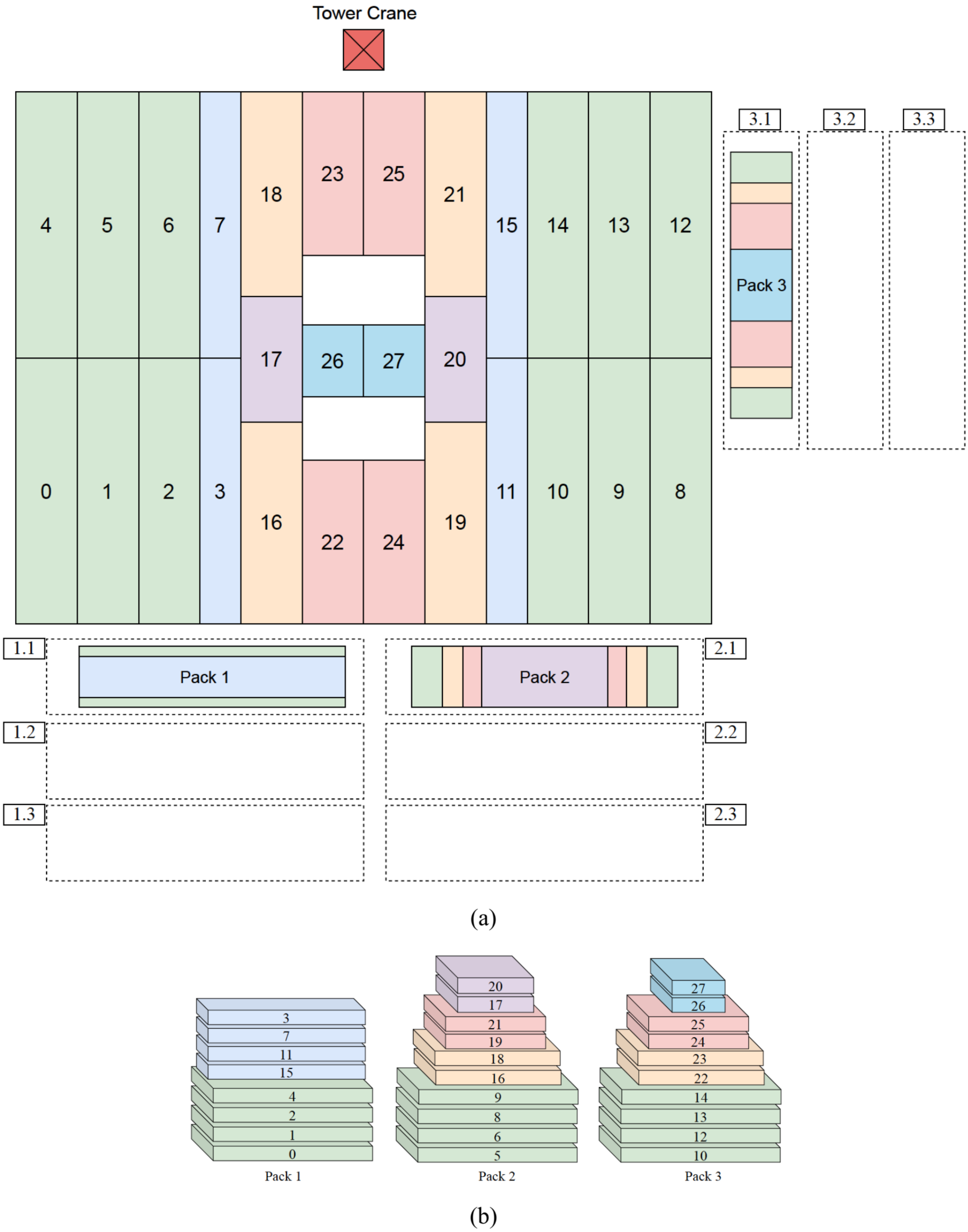



Figure 6.5: Details of the initial problem conditions, including (a) the demand locations and types on the footprint, crane location, staging areas, and stacks of panels, and (b) Details of stacks

The current level's floor includes six different types of panels with specifications as presented in Table 6.1. These panels have been stored on the construction site in three different stacks, prior to the start of the working day as shown in Fig. 6.5. A tower crane with specifications as shown in Table 6.2 starts the lifting operations, based on the priorities given as constant parameters, and decides which panel of the same type as the demand, must be lifted to the assembly location. To test the applicability of the algorithm, three scenarios are defined for the assembly priorities, as visualised in Fig. 6.6 and described below:

1. The installation from the west side of the building footprint and progresses towards the east. The priorities list: [0, 4, 1, 5, 2, 6, 3, 7, 18, 17, 16, 23, 22, 26, 25, 24, 27, 19, 20, 21, 13, 11, 15, 14, 10, 9, 12, 8]

2. The installation from the east side of the building footprint and progresses towards the west. The priorities list: [8, 12, 9, 10, 14, 15, 11, 13, 21, 20, 19, 27, 24, 25, 26, 22, 23, 16, 17, 18, 7, 3, 6, 2, 5, 1, 4, 0]

3. The installation starts from the middle and moves towards both eastern and western directions simultaneously. The priorities list: [27, 25, 24, 23, 22, 26, 21, 20, 19, 18, 17, 16, 13, 11, 15, 7, 3, 14, 10, 6, 2, 9, 5, 1, 8, 4, 12, 0]

4. The installation follows a clockwise rotation pattern. The priorities list: [4, 5, 6, 7, 18, 17, 23, 26, 25, 27, 21, 15, 14, 13, 12, 8, 9, 10, 11, 20, 19, 24, 22, 16, 3, 2, 1, 0]

Table 6.1: Specifications of the panels, corresponding to their assembly demands in the case example

| Colour code | Panel Type | Demand indices | Number of layers | Thickness (mm) | Length (m) | Width (m) |
|---|---|---|---|---|---|---|
| | 1 | 0,1,2,4,5,6,8,9,10,12,13,14 | 5 | 225 | 11.25 | 3 |
| | 2 | 3,7,11,15 | 5 | 225 | 11.25 | 2 |
| | 3 | 16,18,19,21 | 5 | 145 | 8.75 | 3 |
| | 4 | 17,20 | 5 | 145 | 5 | 3 |
| | 5 | 26,27 | 5 | 145 | 3 | 3 |
| | 6 | 22,23,24,25 | 5 | 145 | 6.2 | 3 |

Table 6.2: Specifications of the luffing tower crane

| Characteristic | Value | Characteristic | Value |
|---|---|---|---|
| Minimum working radius (meters) | 4.1 | Luffing duration (minutes) | 1.5 |
| Maximum working radius (meters) | 50 | Luffing speed (rad/sec) | 0.0136 |
| Minimum luffing angle | 15° | Slewing speed (rpm) | 0.75 |
| Maximum luffing angle | 85° | Slewing speed (rad/sec) | 0.078 |

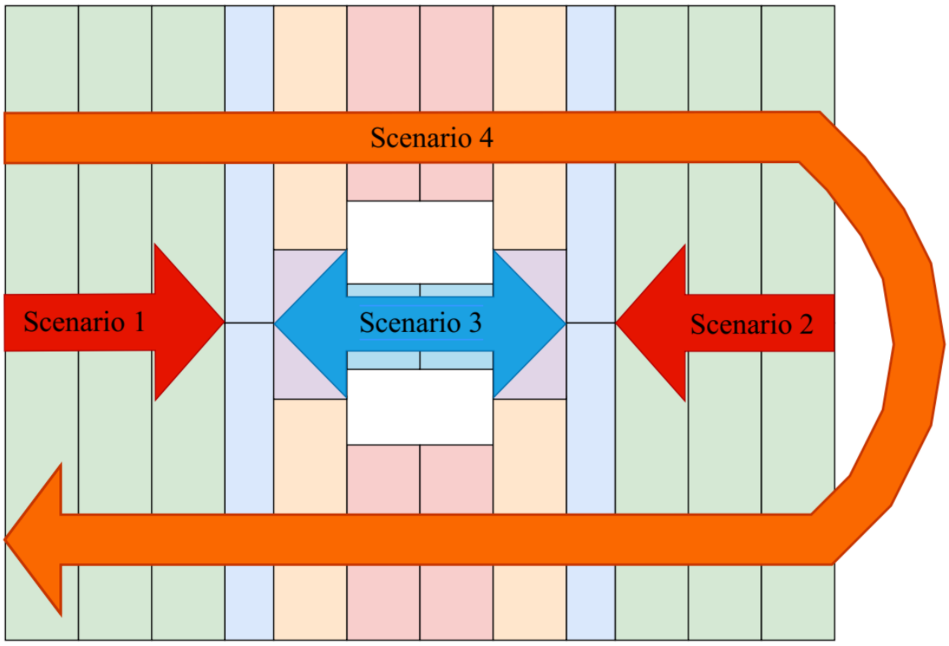



Figure 6.6: Illustration of different scenarios of panel installation priorities

To test the model, the priorities list is imported to the random solution generator in python code as predefined inputs. Then, using the GA, the process of generating random solutions is replicated for all members of the population. The GA then proceeds to apply genetic operators for numerous iterations to converge toward an optimal solution. It should be noted that each scenario yields an optimum solution that meets the assembly requirements imposed by the scenario and the corresponding installation order. Details of the obtained optimum lifting sequence for each scenario are presented below. While these are all feasible and optimum, the best optimum lifting sequence is the one that has the shortest lifting time.

Table 6.3: A summary of the optimisation results for different scenarios (double-handled panels are highlighted in black)

| Scenario | 1 | | 2 | | 3 | | 4 | |
|---|---|---|---|---|---|---|---|---|
| Lift No. | Supply | Demand | Supply | Demand | Supply | Demand | Supply | Demand |
| 1 | 4 | 0 | 4 | 8 | 27 | 27 | 4 | 4 |
| 2 | 2 | 4 | 14 | 12 | 26 | 26 | 2 | 5 |
| 3 | 9 | 1 | 13 | 9 | 25 | 24 | 1 | 6 |
| 4 | 1 | 5 | 2 | 10 | 24 | 23 | 3 | 7 |
| 5 | 0 | 2 | 12 | 14 | 23 | 22 | 21 | 18 |
| 6 | 8 | 6 | 3 | 15 | 22 | 25 | 20 | 17 |
| 7 | 3 | 3 | 7 | 1 | 21 | 21 | 25 | 23 |
| 8 | 7 | 7 | 10 | 13 | 20 | 20 | 27 | 26 |
| 9 | 21 | 18 | 21 | 21 | 17 | 17 | 24 | 25 |
| 10 | 20 | 17 | 20 | 20 | 19 | 19 | 26 | 27 |
| 11 | 19 | 16 | 19 | 19 | 18 | 18 | 19 | 21 |
| 12 | 25 | 23 | 27 | 27 | 16 | 16 | 7 | 15 |
| 13 | 24 | 22 | 25 | 24 | 14 | 13 | 14 | 14 |
| 14 | 27 | 26 | 24 | 25 | 3 | 11 | 13 | 13 |
| 15 | 23 | 25 | 26 | 29 | 7 | 15 | 12 | 12 |
| 16 | 22 | 24 | 23 | 22 | 11 | 7 | 10 | 8 |
| 17 | 26 | 27 | 22 | 26 | 15 | 3 | 9 | 9 |
| 18 | 18 | 19 | 18 | 16 | 13 | 14 | 8 | 10 |
| 19 | 17 | 20 | 17 | 17 | 12 | 10 | 11 | 11 |
| 20 | 16 | 21 | 16 | 18 | 9 | 6 | 17 | 20 |
| 21 | 14 | 13 | 11 | 7 | 4 | 2 | 18 | 19 |
| 22 | 11 | 11 | 15 | 3 | 8 | 9 | 23 | 24 |
| 23 | 15 | 15 | 9 | 6 | 2 | 5 | 22 | 22 |
| 24 | 13 | 14 | 8 | 2 | 1 | 1 | 16 | 16 |
| 25 | 12 | 10 | 6 | 5 | 6 | 8 | 15 | 3 |
| 26 | 6 | 9 | 1 | 1 | 5 | 4 | 6 | 2 |
| 27 | 10 | 12 | 5 | 4 | 10 | 12 | 5 | 1 |
| 28 | 5 | 8 | 0 | 0 | 0 | 0 | 0 | 0 |
| Double habdling | 4 | | 4 | | 1 | | 5 | |
| Total delay (s) | 13688 | | 13670 | | 13167 | | 13753 | |

## 6.10 Discussion

In scenario 4, the installation starts from one side of the building, moves towards the opposite side to install the first row of panels, and then returns to the same side where the installation started. The optimum lifting sequence for scenario 4 appears to lead to the longest installation duration compared to the other scenarios. Similar to scenarios 1 and 2, this can be partly attributed to the wasteful double-handling movements. However, the number of double-handling movements has increased compared to scenarios 1 and 2.

In scenario 3, the installation starts from the middle of the building footprint and then moves towards the building edges in both opposite directions. The total lifting time in scenario 3 is tangibly lower than in the other scenarios. This can be partly attributed to the installation pattern in which the smaller panels are located in the middle of the building layout and hence, must be installed first. Due to the technical requirements of stable stacking for safe transportation, smaller panels are always placed on top of the larger ones, and therefore, this scenario requires the minimum number of unnecessary double-handling operations. This can be different in other projects with different panelisation plans. In other words, starting from the middle may not necessarily be the optimal choice for every project. However, it is obvious that the assembly sequence must be planned with close attention to the panelisation plan of the floor layout, as well as the details of panel storage and stacking.

The results of the proposed framework can be compared with the reported installation speed for CLT buildings. An example is Brock Commons Tallwood House in the University of British Colombia, Canada [248, 249] which has been named as one of the fastest CLT buildings constructed thus far. The project is an 18-storey timber building using a structural system of timber floors and columns, with a net floor area of $722m^2$, and a total number of 29 floor panels on each level. This project can be a good industry benchmark for comparison with the current study's example case, which has a $722.4m^2$ floor area and 27 floor panels.

The published data of the Brock Commons show different panel installation speeds as the project progresses. However, a rough estimate of 6 to 12 minutes for the installation of different panels has been reported. By assuming an average of 9 minutes for installation of each panel, the total lifting time equates to 4 hours and 21 minutes. The total lifting time for this study's case in scenario 3 is 3 hours and 40 minutes, which is 15.7% faster than the Brock Commons installation speed as the industry benchmark. If the additional two panels of Brock Commons are factored in, the example case in the present study is still installed faster by 9.46%. This shows that the developed framework can be utilised to plan for the efficient and orderly installation of prefabricated systems.

## 6.11 Conclusions

Careful planning of onsite assembly plays an important role in achieving overall efficiency in prefabricated building construction. In this operation, lifting machinery is the leading resource and must be utilised optimally for an efficient lifting sequence to avoid bottlenecks in the smooth flow of onsite installation.

This chapter presented an optimisation framework for scheduling crane operations that enables efficient lifting and installation of panelised prefabricated systems in multistorey buildings. The study focused on the construction of MT buildings as a sustainable form of prefabrication that has been increasingly adopted over the past decade. The framework considered conditions including on-truck stacking pattern, onsite staging and handling limitations, and installation requirements of various building layouts. In addition, it incorporated the crane's motion kinematics to ensure precise estimation of different lifting tasks and alternative lifting sequences. The framework employed a stepwise approach to generate feasible crane schedules consecutively and identified the optimum solution using an evolutionary approach. Comparisons between a real-world case as the benchmark and the results of this optimisation framework showed that the proposed model could outperform a relatively efficient and reputable panelised CLT project.

The present research makes contributions to the MC literature by introducing efficiency to the onsite production operations of the CLT construction as a highly prefabricated building system. Higher efficiency can be attained from the offsite construction systems such as CLT if they are accompanied by efficient onsite operations. In addition, the current research incorporates operational details associated with the CLT construction, such as stacking rules and dynamic supply points, exploiting these complexities to achieve even more optimality in the lifting process.

The results of this research can be used by building construction companies that adopt prefabricated and industrial construction methods to uplift their onsite efficiency to the level that they can attain in the offsite production stage. While the case example is a panelised MT building, the same principles and conditions surround other forms of prefabrication with various materials, including precast concrete and prefabricated steel modules. This, however, requires further research to examine whether adjustments in the proposed model are required. The users can also implement and test the proposed model to evaluate different scenarios and identify the best assembly sequence in buildings with complex and non-rectilinear layouts. In addition, different configurations of the construction site, including the staging areas, crane location, and panelisation details, can also be set up and tested for optimal lifting.

# Chapter 7

## Conclusions

The weak link between production and design is a major barrier to properly adopting MC strategies in prefabricated building projects. This barrier persists due to the absence of a design system that is aware of the SC processes and develops designs that are optimal for production processes (section 1.2). To address this gap, this thesis presented a design and planning support framework for MC in CLT building projects. This framework aims to integrate SC processes into the design and planning stages to improve mass-customisability in a prefabricated construction setting. Section 1.4 determined two areas of focus for this research to achieve this objective, i.e., the design work and the onsite operations planning. Thus, the thesis took a step-wise research approach, with each step tackling different parts of the issue.

The thesis identified four key challenges negatively affecting the implementation of MC strategies in the defined scope discussed in section 1.5. These challenges include:

- Absence of a conceptual framework for integration of SC processes, as well as customer's input in a design system.
- Temporary nature of the construction SCs, leading to poor design knowledge sharing.
- The interrelations between technical design details and architectural specifications, lead to difficulty in controlling both MP and customisation objectives and maintaining a **balance** between the two.
- Inefficient onsite installation operations offsetting the productivity gained by prefabrication and mass-custom designs.

A set of systematic studies were then conducted to address these issues, reported in detail in chapters 3, 4, 5, and 6. In particular, chapter 3 introduced a conceptual framework for an integrated design support tool to achieve the goals of MC. This framework identifies the information details and information flow that are needed from the SC participants (i.e., design team, construction, transportation and manufacturing) and the customers, in order to address the design knowledge-sharing issue.

To address the imbalance issue that exists between MP and customisation, the research emphasised the development of a solution from the preliminary design stage. This solution must systematically automate the design process to enable MC along the SC, particularly during offsite manufacturing. Chapter 4 presented a design support tool that targets the preliminary design of the CLT load-bearing system. The focus was placed on CLT mainly due to its increasing market uptake, sustainability benefits, and more importantly its machinability. Wall elements were chosen as critical structural components, directly affecting the architectural layout, and thus, building customisability. The best balancing strategy was recognised as increasing manufacturability in these elements while maintaining architectural flexibility. This required a sophisticated mathematical model that can successfully lead to an optimal CLT design solution.

Chapter 5 addressed the MC balancing issue by solving the previous problem on a larger scale. Further, to alleviate the design knowledge-sharing issue, as well as to verify the applicability of the model, a framework was presented for data transfer to BIM software. Both chapters 4 and 5 addressed the temporary SC issue by incorporating DfMA guidelines in the optimisation model. These guidelines are general and independent of the supplier, making design improvements possible regardless of the supplier's specific production variables.

Finally, to ensure overall productivity and to make sure that the optimal structural elements designed in the previous steps are installed efficiently, an onsite operations planning tool was developed and presented in chapter 6. The lifting machinery (i.e., cranes) was found to be the bottleneck for installation operations since assembly of heavy prefabricated elements is not possible without them. Factors adversely affecting the crane operations were found to be wasteful and unnecessary crane motions in an unloaded state, as well as double handlings due to poor crane scheduling and storage of CLT panels.

In the remaining sections of this chapter, we thoroughly examine each element of the research that was presented in chapters 3, 4, 5, and 6. Our examination serves the following purposes:

1. To discuss the utilised methodology, tools and techniques, and their suitability for the problem

2. To outline the contributions of each chapter in terms of addressing the research gap, responding to research questions, and achieving the overall aims and objectives that were defined in chapter 1.

3. To discuss the practical and research implications of each chapter's contributions.

4. To outline the limitations of the methodologies presented in each chapter and provide recommendations for future developments and improvements.

## 7.1 Conceptual framework for integrating design and the supply chain

The initial step in the overall research process involved developing a framework for executing mass-customised buildings via a practical design support system in the prefabricated construction context. Chapter 3 provides a conceptual framework for a design support system, details about the type of information needed from the SC participants (i.e., design team, construction, transportation and manufacturing) and the customer.

### 7.1.1 Methodology

This part of the research uses the development of a conceptual framework, to set the foundation for a series of subsequent applied studies. The importance of a conceptual framework lies within the nature of the defined scope of the study, including a wide range of research areas, and production processes. To paint a clearer picture of a rather realistic than ideal scope, towards which the quantitative research is usually inclined [250, 251], and guide the research to more awareness of the variables to include in the research, a conceptual framework is crucial to develop [252].

### 7.1.2 Chapter's efforts to fill the research gap

The absence of a framework for transferring knowledge from the MC and the customer to the design work presents a key challenge in adopting mass-customisation strategies in the building industry. The literature also comes short in analysing different tools and techniques and how they can come together in an integrated system that improves mass-customisability. Chapter 3 addressed this gap successfully by presenting a conceptual framework that can be used as the basis for designing mass-customisation frameworks. This framework provides a comprehensive overview of similar studies in the area of MC. The framework also presents different modularisation and automated design techniques, making it a practical guideline for practitioners interested in implementing the mass-customisation strategy.

### 7.1.3 Chapter contributions to research and practice

**Contribution to research**

This study introduces various modularisation tools and techniques necessary for analysing information gathered from stakeholders. The outcome of this analysis is a catalogue of custom designs that align with the production SC requirements. The proposed framework serves as a practical foundation for future research in the field of MC-oriented design support tools.

**Contribution to practice**

For industry practitioners, this research provides a detailed, step-by-step guide to developing design support tools that help create catalogues of designs at early design stages. The framework emphasises specific variables in the supply chain that hold the highest significance when developing custom modular design options. This project-specific system can be utilised by modular building developers and their suppliers to foster a collaborative SC reflected in the design work.

Economically, using such a system could cause vertical integration in the SC, by apprising the design work of the variables of the SC participant's variables. As advocated in the thesis, this could mean cheaper production due to higher efficiency in SC processes, as well as higher customisation due to the variety offered through design catalogues. In total, using systems similar to the one proposed could not only cut building construction costs but also increase the value of the final product, which means more profit for the building developers.

### 7.1.4 Chapter's response to the Research Questions

**Question 1**

**How to mass-customise the design for optimal manufacturing?** Chapter 3 has made an effort to provide a guideline for creating a bridge between the two counteracting ends of the MC, being the design and the SC. As a conceptual framework, this chapter successfully identified different participants in the production SC, and their important variables that affect either mass-producibility or customisation of the final building. Further, the chapter suggested a detailed footprint for developing a design support tool that integrates all of the components into the design work, through a knowledge-sharing procedure.

**Question 2**

**How to optimise the onsite operations to make sure that our MC designs are installed optimally?** At this step of the research, as well as the next two chapters, the onsite operations were out of the study's scope. This issue has been thoroughly addressed in chapter 6.

### 7.1.5 Methodological limitations and recommendations

The conceptual framework presented in Chapter 3 merely discusses general supplier variables and parameters and is limited in terms of technical details. Due to this shortcoming, important variables and parameters from the suppliers and detailed customer requirements might be overlooked. Further, the framework assumed a catalog-based customisation offering strategy, which is overly focused on customisation and not rich in technical details. Future studies can develop similar frameworks emphasising the suppliers' side, considering more technical variables. For instance, future frameworks can include information about prefabricated concrete systems, such as mold prices, loading details, and how waste correlated to the building design. The customisation strategy also needs improvements since offering various options in the form of catalogs requires various sub-products, which is not economically efficient in construction. An example of such strategies is presented in chapter 4.

## 7.2 Design support tool for mass-customising CLT structures

Chapter 4 proposed a design support tool for MC of CLT buildings. The tool generates mass-customised designs for panelised CLT projects and finds the best geometries for CLT structural walls. These geometries incur minimum material waste while maintaining maximum standardisation to minimise process waste. Results of an implemented case study indicated that significant material waste reductions (up to 20% for the presented case) could be achieved by adopting the proposed optimisation algorithm while decreasing component variety (from five to three in the case presented). The level of benefits may vary from one case to another, depending on the component prices as well as the architect's initial layout preferences, which affect the wall panel thicknesses. Therefore, this information must be carefully identified and considered as input variables in the optimisation algorithm.

### 7.2.1 Methodology

This chapter has used a meta-heuristic algorithm (GA) to explore a large number of different designs quickly, rate them based on predefined criteria and re-generate better-fitting design options. The GA is popular among studies that address generative design problems since the solution space (i.e., the number of design alternatives) is very large, requiring inclusiveness as well as search speed [253]. Among different methodologies, GAs have proven capability in both searching large solution spaces, and computation time [171]. The literature review sections of both Chapters 4 and 5 introduce examples of research that have successfully implemented this algorithm for the purpose of automating the design.

### 7.2.2 Chapter's efforts to fill the research gap

As recognised through a literature review, there is a gap in the previous studies, regarding an integrated system that considers various production variables when generating designs at its different stages i.e., conceptual, preliminary, and detailed structural and architectural designs. The current research makes such a system operational to an extent by taking manufacturing variables into account. In the context of the building industry, where scattered and temporary SCs are prevalent, the existence of such tools is advantageous. It is specifically beneficial since it considers the production variables and suppliers' limitations without reliance on direct engagement with the suppliers. This tool is utilisable at the early stage of design without compromising the flexibility and customisability of the architectural layouts.

### 7.2.3 Chapter contributions to research and practice

To implement mass-customisation strategies, an automated design system capable of generating feasible design values that maintain the balance between mass-production and customisation is required. A system able to explore technical specifications and architectural parameters simultaneously has not been developed in the literature. chapter 4 addressed this problem by incorporating manufacturing and assembly processes into a relatively custom design context. The optimal design values found by the model successfully decreased the production wastes while preventing a decline in the customisation element. This result will arguably increase the overall productivity by decreasing the overall costs (as established in section 2.1.2).

In practice, CLT manufacturers already supply standard panel sizes, most of the time at a discounted price, to encourage standard off-the-shelf ordering. The problem, however, is that the building industry of Australia favours customisation, and thus, this standardisation strategy does not work well in the real world. This research's aim, therefore, was to find custom designs with minimum waste. Therefore, this research does not advocate the full standardisation of panels; instead, it intends to enable mass customisation.

**Contribution to research**

This research can be a starting point for research that consider the production variables in the design work while being aware of both structural and architectural requirements. The approach of this research is to numerically consider manufacturing, architectural and structural variables and constraints is a novelty in the generative design research area, and can provide insights into future developments. These developments can address further integration of variables from other SC participants, such as transportation and onsite logistics.

**Contribution to practice**

Using this model, the designer can generate structural wall layouts that are more uniform in shape and less wasteful in terms of billet usage. The model's adaptable structure enables it to be adjusted to the new problem conditions in the case of some panel manufacturers who provide a more affordable set of made-to-stock standard panel sizes. Additionally, this model enables the architect to test various structural wall preferences and obtain a preliminary estimate of the production wastes before deciding on design revisions.

The developed framework is a design-support tool that incorporates SC processes into the design stage with the goal of enhancing the final building product's mass-customisability. The presence of such tools is advantageous in the context of the housing industry, where dispersed and temporary SCs are common. The fact that it takes into account production variables and supplier constraints without relying on direct engagement with the suppliers makes it particularly advantageous. The flexibility and adaptability of the architectural layouts are not compromised by using this tool at an early stage of design.

Economically, due to the high price of the CLT panels, the waste reduction will decrease the panel manufacturer's costs, and the standard geometries of the panels designed using this tool will ease the entire SC processes. These results will both contribute to reducing the overall cost of building construction, which will help the developer offer a fairly custom dwelling for lower prices, and gain a competitive advantage over the competition in the market.

### 7.2.4 Chapter's response to the Research Questions

**Question 1**

**How to mass-customise the design for optimal manufacturing?** According to this research, the best point of entry in the design work for implementing MC, at the current stage of the industry with dispersed SCs, is the preliminary design. At this stage, the interior layout is established, so the design manipulations will have minimum impact on the customisation factor. Also, the structural elements are claimed to be the ones with the most potential for mass-customisability since they involve a large proportion of the building's volume and material costs, while their shape is not important to the final user (as the customisation element.). Having this balance between MP and customisation maintained, the research also proposes a passive method for interacting with the architectural design team, as well as the manufacturer, to take their preferences and parameters into account when generating feasible designs.

**Question 2**

**How to optimise the onsite operations to make sure that our MC designs are installed optimally?** Similar to the previous chapter, this question and the objectives defined based on it, is out of the research scope. However, the standard nature of the elements that will be generated as the output of this research will contribute positively to all building production processes, including transportation and onsite assembly.

### 7.2.5 Methodological limitations and recommendations

The model presented in Chapter 4 is merely a tool at this stage, and the limited scope of applicability can be enumerated as its major limitation. In addition, the application of the current model is limited to a specific structural system (i.e., CLT) and considers a limited number of design objectives. Efforts to develop integrated design tools similar to this model for other structural systems are a potential area for future research. In addition, the model proposed in Chapter 4 is not intended to serve as a design platform; rather, it is merely a design tool.

Further research, such as the one presented in Chapter 5 are necessary to integrate such tools into a more holistic design platform (Chapter 3 provides a framework for such platforms). Similar studies can be performed for other organisational contexts, where the suppliers are determined, and more details of their processes can be entered into the model. Other potential studies should perform more accurate market studies to identify the optimal level of customisation for overall maximum revenues.

Further, the model's adaptability for non-rectilinear building layouts or layouts with bidirectional structural wall systems also needs more study. Future research could also focus on adding more prefabricated building systems to the model, adding more design specifics to the model to reflect different real-world design scenarios, and enhancing the model by including a wider range of factors related to transportation and assembly processes.

## 7.3 Automated design framework for mass-customising CLT buildings

Chapter 5 integrated an improved version of the previously developed tool in a design support framework. The framework uses BIM software as a design knowledge-sharing platform across the SC, that uses file formats that are common among different production practices. Implementation of the framework on a large-scale case project indicated significant performance improvements (up to 19% waste reduction) in comparison to industry benchmarks. In addition, the framework could successfully generate a visual model of the building, along with a bill of quantities.

### 7.3.1 Methodology

This chapter of the research employs a similar methodology to the previous section and combines it with a heuristic algorithm. The addition of the heuristic algorithm (i.e., greedy algorithm) is due to its efficiency in solving the BPP, which is defined as a part of the mathematical formulation. In addition, due to the large number of entities and their variables involved in the optimisation, a python data structure including classes and methods has been proposed. Further, the research uses Autodesk Revit which is a powerful BIMplatform and enables the high potential for communicating data among SC participants. Lastly, the chapter also proposes a data transfer procedure, to create a connection between optimisation results and the BIM platform, and generates a graphical model of the building and bills of materials to show the practicality of the research.

### 7.3.2 Chapter's efforts to fill the research gap

The chapter introduced a design support framework which integrates a more complex version of the design tool proposed in Chapter 4 into a modified version of the framework introduced in Chapter 3. The contribution of this chapter is providing a practical design framework, which utilises common software in the industry, to implement the idea of SC integration. In this research, production variables are introduced as variables into the generative design algorithm, and the results are transferred into Autodesk Revit, where a visual model of the final structure, along with precise bills of materials is generated.

### 7.3.3 Chapter contributions to research and practice

The issue of a weak information connection between the design and other participants was also covered in Chapter 5. By enhancing the performance of the optimisation algorithm and connecting it to a BIM platform, this chapter broadened the applicability of the design optimisation tool even further. With the help of this framework, complex issues can be quickly optimised, and BIM software can receive results. By providing early design information in a standard format, the BIM platform can improve the SC's weak information link. In the following, the contributions of this research to both research and practice are separately enumerated.

**Contribution to research**

This research can provide academia with an example of how the manufacturing parameters can be effectively integrated into the design work using the common tools that are currently used in the market. Also, the research opens new research opportunities to the researchers studying the areas of MC, SC integration, and generative design, by introducing a working example of an integrated design system.

**Contribution to practice**

To create a design with the best possible manufacturing and assembly performance, the supply side and design teams should collaborate closely. However, due to the high variability of the building products in the project-based environment of construction, this ideal might not be entirely attainable.

The temporary SCs that result from this variability makes early planning and communication with suppliers challenging for the design work. Since these regulations are not project-specific, implementing them at the design stage ensures improvement in production processes.

The proposed model is advantageous in the initial stages of design because it requires little design work and produces design solutions quickly. By giving the designer a way to share early design solutions with other project participants, the generated BIM model helps the designer collaborate with them more effectively. It is anticipated that the BIM model will speed up the feedback process from the beginning and assist in identifying potential obstacles to the DfMA implementation. The proposed framework also aids manufacturers in coordinating their manufacturing procedures with the initial design requirements.

Economically, this framework brings about all the benefits of the methodology proposed in chapter 4, since it has the same mechanism of waste reduction and standardisation in CLT panels, and the computational power to solve larger scale problems. In addition, the connectivity of the optimisation model to a BIM platform, gives the users the capability to produce graphical models and bill of materials at very early stages. These capabilities will increase the chances of the company winning tenders by having early estimates of an optimal panelisation, and its related costs.

### 7.3.4 Chapter's response to the Research Questions

The integration that needs to be achieved in order to attain the goals of MC in the construction industry in its current state, needs practical frameworks that are applied using the currently available tools and software. This research contributes to this objective by both theorising and illustrating the applicability of a proposed integration system through a real-world project application.

**Question 1**

**How to mass-customise the design for optimal manufacturing?**

The integration achieved in this chapter aims to respond to this question by addressing the preliminary design stage as the most suitable bridge between the design work and production processes. This choice responds to the question of the design stage and the components suitable for addressing the MC balance It focuses on structural walls and further develops the capabilities of the model presented in Chapter 4 by solving it on a larger scale. The research also introduces BIM software, which has a universal file format that can be used as a shared language among different SC participants.

**Question 2**

**How to optimise the onsite operations to make sure that our MC designs are installed optimally?**

Similar to the two previous chapters, this chapter also does not focus on onsite operations. However, by increasing the practicality of the design optimisation model, and extending it to generating actual design specifications, it paves the road to taking the onsite operations into account and integrating these operations' variables in the design.

### 7.3.5 Methodological limitations and recommendations

The shortcomings associated with the previous section can also be cited for the framework introduced in chapter 5. In addition, the chosen arrangement of the load-bearing walls is a one-way spanning system, and this assumption may not be applicable in other cases. Although this system is the most common case in mass-timber buildings and is suggested as a better- performing solution, it can be cited as a limitation of this research.

Thus, one of the most important future developments that have to be achieved, in order to make this design system more generalisable and practical, is modifying it for other construction systems with different materials and installation processes. Other potential areas of improvement include incorporating more details in terms of design specifications and considering wider aspects of the supply-chain processes. Lastly, As mentioned in the previous subsection, one area with potential for development, to achieve higher levels of MC is to perform research on adding variables from other production processes into an integration platform such as the one presented here.

## 7.4 Ensuring optimal onsite installation of mass-customised CLT systems

An algorithmic process was developed in chapter 6, to optimise the onsite installation operations for a number of CLT installation tasks. The developed model generates feasible lifting schedules for a single tower crane operating under different site conditions. The algorithm considered conditions including on-truck stacking pattern, onsite staging and handling limitations, and installation requirements of various building layouts. In addition, it incorporated the crane's motion kinematics to ensure precise estimation of different lifting tasks and alternative lifting sequences. The algorithm was implemented on an example case with 28 lifting tasks on a single floor level, which resulted in a significant amount of improvement compared to an industry benchmark.

### 7.4.1 Methodology

The research proposes a lifting sequence optimisation for the specific setting of CLT buildings. A GA is chosen as the solution search method in this chapter due to the complexities introduced to the solution space of the problem, from CLT-specific conditions. The GA, as the optimisation algorithm, is combined with a precise lifting time estimation algorithm, making a quick solution search process necessary due to computational complexity.

### 7.4.2 Chapter's efforts to filling the research gap

This chapter effort to fill the gap of the weak link between the SC and the design work by presenting another piece of the puzzle that can be potentially integrated into the previous framework presented in chapter 5. Onsite operations are a major part of the overall costs in the construction of panelised MT buildings since they use a lot of expensive lifting equipment and labour. The present research makes efforts to optimise the lifting operations while taking the order of loading of the panels on the truck and their arrival into account. In essence, the algorithm solely increases the efficiency of onsite panel installation by considering the interchangeability, storage limitations and access restrictions for different panels. However, the ultimate goal is to integrate this algorithm with integrated systems such as the one presented in the previous chapter.

### 7.4.3 Chapter contributions to research and practice

**Contribution to research**

In a prefabricated construction context, with efficient factory production processes, the inevitable onsite installation operations pose a critical productivity challenge. This gap has not yet been addressed in the literature for various systems with specific transportation and storage conditions. Chapter 6 aimed at addressing the problem of onsite inefficiency by developing an installation planning framework for CLT panels. Since onsite operations are a major source of inefficiency in prefabricated systems, the presented model enables efficiency by minimising the delays in assembly operations. In addition, the current research incorporates operational details associated with the CLT construction, such as stacking rules and dynamic supply points, exploiting these complexities to achieve even more optimality in the lifting process. Therefore, this research opens new doors for researchers in the area of onsite logistics, especially the ones dealing with material lifting problems, by introducing factory-related parameters, as well as different material- and construction system-specific considerations that must be made.

**Contribution to practice**

Comparisons between a real-world case as the benchmark and the results of this optimisation framework showed that the proposed model could outperform a relatively efficient and reputable panelised CLT project by up to 10%. This research, therefore, provides construction practitioners by providing them with a tool that can help them better adopt prefabricated and industrial construction methods to uplift their onsite efficiency to the level that they can attain in the offsite production stage.

Economically, in a CLT building system, a large proportion of project costs are associated with the onsite installation of the panels since they utilise expensive machinery and workforce. Having unnecessary delays eliminated from these processes could bring about economic benefits by cutting these costs. Also, the proposed model considers the double-handlings required because of the CLT specific storage and handling details, which are also taken into account in this model. Generating optimal lifting plans that reduce these double handlings will further decrease the overall operational costs. Lastly, utilising the model presented in this research will reduce the overall project duration, ensuring on-time project completion and preventing loss of market value.

### 7.4.4 Chapter's response to the Research Questions

**Question 1**

**How to mass-customise the design for optimal manufacturing?**

This chapter partly responds to this question by addressing the commonly overlooked side of the MC. The literature usually uses different modularisation methods and design innovations in attaining the goals of MC. However, it is often the case that a seemingly optimal modular design will face assembly difficulties due to neglecting the real-world operational complexities that different modular systems can face onsite. Based on the findings of this research, the response to this question is that the design, especially how the design is panelised (separated into panels) can have a major effect on the efficiency of onsite installation. A simple rule of thumb suggests that the larger the panels are, the less time-consuming their installation will be. However, the results of our research pose that the installation sequence must be highly in line with the panels' stacking on trucks; the installation sequence must be planned so that the smaller panels are installed first. This is due to the nature of stacking of CLT panels, which will require double handling of the smaller panels on the top of stacks if the previous suggestion is not followed.

**Question 2**

**How to optimise the onsite operations to make sure that our MC designs are installed optimally?**

The research answers this question by recognising the bottleneck of onsite construction operations, in prefabricated timber systems. Since these systems consist of several heavy elements that need to be installed, construction machinery is the resource that can cause the most delays, if their operations are not properly planned and managed. Again this part of the research chose the structural elements as the most critical in terms of onsite lifting transportation, due to their heavy and bulky nature.

To tackle the problem of inefficient onsite operations, this research has noted the lift delays, and double handling operations performed by the lift equipment, as the most crucial sources of productivity loss. Specifically, the nature of onsite storage and stacking of the timber panels, if not aligned with the installation plan, can lead to numerous double-handling operations. One strategy to alleviate that can be either by changing the panelisation of the building, which is out of the scope of this research. The other effective strategy could be optimising the sequence of installation so that the panels on top of the stacks are prioritised, which has been successfully demonstrated by this study.

### 7.4.5 Methodological limitations and recommendations

The main limitation of the model presented in Chapter 6 is the CLT-specific assumptions regarding the stacking requirements on both the trucks and the storage areas onsite. The validity of these assumptions for other planar prefabricated systems requires further investigation. In addition, the model in its current form is only applicable on construction sites with a single crane, which is a hindrance to its generalisability. Future studies can examine the adjustment of this model to other building systems, such as precast concrete and prefabricated steel systems. Further developments in the model to make it applicable in sites with multiple cranes are also a potential area for future research.

The research presented in this thesis did not aim for commercialisation. Based on the guidelines of Technological Readiness Level (TRL)s, a technology requires 9 levels of maturity to be ready for full commercial deployment. The current research has only passed TRL 2, i.e. (1) Basic research, (2) Applied research, and requires more case studies to fully complete TRL 3, i.e.(3) Critical Function or Proof of Concept Established. While this research has paved the way for commercialisation, interested researchers and industry practitioners must conduct comprehensive lab tests, prototypes and pilot tests in order to commercially deploy the tool developed in this research.

# List of Acronyms

| | |
|---|---|
| **ACO** | Ant-Colony Optimisation |
| **ATO** | Assemble-To-Order |
| **BIM** | Building Information Model |
| **BPP** | Bin Packing Problems |
| **CLT** | Cross-Laminated Timber |
| **CODP** | Customer Order Decoupling point |
| **CNC** | Computer-Numeric Control |
| **CSP** | Cutting Stock Problem |
| **DfMA** | Design for Manufacture and Assembly |
| **DP** | Design Parameter |
| **DPs** | Design Parameters |
| **ETO** | Engineer-To-Order |
| **GA** | Genetic Algorithm |
| **GAs** | Genetic Algorithms |
| **G-GA** | Greedy-Genetic Algorithm |
| **ILP** | Integer Linear Programming |
| **MC** | Mass-Customisation |
| **MIP** | Mixed-Integer Programming |
| **MP** | Mass-Production |

| | |
|---|---|
| **MT** | Mass-Timber |
| **MTS** | Make-To-Stock |
| **MTO** | Make-To-Order |
| **NCC** | National Construction Code |
| **SC** | Supply-Chain |
| **SCM** | Supply-Chain Management |
| **TRL** | Technological Readiness Level |

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